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Noise Reduction System for General Aviation Aircraft, Phase II

Sangvavann Heng, Edwin P. Stankiewicz, and Andrew J. Sherman
Ultramet, Pacoima, California

November 2005

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Note that at the time of writing, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names may appear in this report.

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GLOSSARY

Term	Definition
ARC	Ames Research Center
AWOS	Automated Weather Observing System
CO	carbon monoxide
CO_2	carbon dioxide
CVD	chemical vapor deposition
dB_A	A-weighted decibels
DFRC	Dryden Flight Research Center
EPA	Environmental Protection Agency
FAR	Federal Aviation Regulation
GA	general aviation
HC	hydrocarbons
hp	horsepower
ID	inner diameter
inHg	inches of mercury
LeRC	Lewis Research Center
mph	miles per hour
NASA	National Aeronautics and Space Administration
NO_x	nitrogen oxides
O_2	oxygen
OD	outer diameter
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
ppi	pores per linear inch
ppm	parts per million
rpm	revolutions per minute
RVC	reticulated vitreous carbon
SBIR	Small Business Innovation Research
SiC	silicon carbide
tpy	tons per year

1. INTRODUCTION

This is the final technical report submitted by Ultramet, Pacoima, CA 91331 to NASA Lewis Research Center (LeRC), Cleveland, OH 44135 under SBIR Phase II contract NAS3-27633. The period of performance was from 1 February 1995 to 31 May 1998. The principal investigator was Andrew J. Sherman, supported by Sangvavann Heng and then Edwin P. Stankiewicz as project managers. The LeRC project manager was Richard P. Woodward.

In this project, durable, high temperature ceramic foams were evaluated as potential passive broadband noise absorber/baffle materials for reciprocating piston general aviation (GA) aircraft engines. In the Phase I project, a ceramic foam-based combined dissipative/reactive muffler design proved its potential for successfully reducing the size, weight, induced backpressure, and noise of GA aircraft engines. However, tuning the combined muffler design for specific engine noise reduction proved highly complex and difficult, requiring analytical tools that did not as yet exist. In Phase II, numerous test methods were developed to screen various newly developed ceramic foam-based muffler designs and evaluate their acoustic characteristics. More than 30 prototypes representing actual muffler designs and containing Ultramet ceramic foams were fabricated and characterized. Methods for acoustic evaluation included insertion loss bench, dynamometer, ground, and flight testing. Based on the results of these tests, Ultramet ceramic foams were shown to be generally effective as broadband noise absorbers at frequencies above 800 Hz, particularly for larger GA aircraft engines. The most promising ceramic foam-based muffler prototype reduced the noise emitted by a Continental O-200 engine by up to 14 A-weighted decibels (dB_A) relative to the stock exhaust system (a short, straight pipe). Varying the ceramic foam design parameters yielded variations of as much as 5 dB_A in the induced sound pressure levels, but did not affect the frequencies reduced. However, the backpressures induced by the majority of the ceramic foam muffler prototypes were well below maximum allowable levels. Given their light weight and compact size (including required canning and inlet/outlet pipes), these mufflers can be retrofitted under the cowlings of GA aircraft.

2. BACKGROUND

Strict adherence to FAR Part 36 Stage III regulations requires noise reductions on the majority of general aviation aircraft. Any new aircraft certified or any modification to an existing aircraft must show compliance with this regulation. The majority of aircraft noise in the GA class arises from the propeller and the engine exhaust, with the relative importance of each source dependent on the engine size (horsepower, or hp) and propeller characteristics (number of blades, disk area and disk loading, aerodynamic efficiency, and tip speed). For most aircraft with powerplants of <250 hp, which comprises the vast majority of GA aircraft, engine noise is equivalent to or exceeds propeller noise and must be decreased to significantly reduce aircraft noise and come into compliance with current aircraft noise regulations in order to recertify an aircraft. While the noise problem is not as great in magnitude for smaller, lighter aircraft (noise levels rise roughly with horsepower squared) as it is for commuter, business, and commercial aircraft, the number of flights (takeoffs and landings) per day and the number of aircraft in the GA category are substantially higher than all other categories combined. Also, while the smaller, lower horsepower GA aircraft may not generate as much noise as larger aircraft, they are generally heard more often by the public because of their lower flight altitudes and slower climb speeds.

A typical GA aircraft engine generates between 120 and 150 decibels of sound through the combination of engine and propeller noise. This level severely exceeds OSHA standards for limited duration exposure and creates a substantial nuisance in and around airports, in addition to presenting a health hazard to pilots, mechanics, and crew working in and around these aircraft. This is similar in magnitude to unmuffled automotive and other vehicular engines, and has required the addition of acoustic filters (mufflers) to reduce noise impact in the community surrounding the airport. This trend is being extended to GA aircraft, to which typical public response has been to place restrictions (in terms of monetary costs, fines, flight limitations, flightpath restrictions, and even grounding) on the general aviation community. Tremendous effort, time, and expense have been directed at reducing noise from commercial, business, and short-haul commuter aircraft noise; however, almost no effort has been expended to reduce noise from the smaller GA aircraft, with the exception of cockpit and cabin noise reduction efforts conducted by the major airframe manufacturers.

Engine noise reduction through the use of acoustic filters or mufflers presents an extremely difficult problem, however, and cannot be solved by the simple solution of applying off-the-shelf automotive or diesel-type muffler systems due to backpressure, volume, weight, and size constraints that are much more critical for GA aircraft application. Because of the low frequencies that must be silenced (typically 40-150 Hz fundamental frequencies), conventional mufflers require extremely large sizes/volumes or excessive lengths to successfully attenuate the engine noise. For example, at a 42-Hz fundamental frequency, the wavelength of sound in the exhaust is 38 feet, requiring a muffler at least 9 feet long to attenuate noise using resonant techniques.

Alternately, the muffler volume using current diesel engine standards (similar in frequency and displacement to aviation engines) would require a volume approximately six to ten times the total engine displacement, or close to 3000 in^3 (excluding the tailpipe) enclosed volume for an average-size aviation engine. This is roughly the volume enclosed in a 10" diameter pipe almost 4 feet long (about the size of an exhaust stack on a truck), excluding the volume of a 2" diameter internal passage. In fact, the only well-known GA aircraft muffler system, produced for the Beech

Bonanza A36 equipped with a Continental O-520 engine, runs almost the entire length of the fuselage, changing the structural, drag, and performance characteristics of the entire aircraft. Furthermore, the application of conventional two- and three-pass automotive-type mufflers is unacceptable due to the 6 to 15 inches of mercury (inHg) backpressure that these systems induce.

For these reasons, new and innovative acoustic filter/muffler designs must be developed and introduced into the general aviation community in order to meet the specific noise reduction demands being made on the industry. These muffler designs must be small in volume, low in weight and performance impact (i.e., backpressure), relatively low in cost (compared to retrofits/upgrades required for larger aircraft), require minimal or no maintenance, and preferably easily retrofittable into the current fleet of private aircraft at minimum cost.

2.1 Aircraft Noise Sources and Relative Contributions

Noise in GA aircraft generally arises from three sources: the reciprocating piston engine (vibration and exhaust noise), the propeller (rotational, thrust, and vortex noise), and flight aerodynamics (aerodynamic noise). Of these three sources, propeller and engine noise generally far outweigh all other noise sources on subsonic propeller-driven aircraft.

The power levels, frequency, and spatial distributions are different for each noise source, and the summation of all noise sources results in the total radiated noise level. The two key noise sources considered in this project (and dominant for aircraft) were the propeller and engine. In general, propeller noise increases in proportion to the square of engine horsepower, while engine noise increases in direct proportion to engine power. This general trend shows that for smaller aircraft (typically <200 hp), engine noise dominates the total noise output, while for larger aircraft (>300 hp), propeller noise is the major noise source. For aircraft in the 200-300 hp class, engine and propeller noise are of similar magnitude.

The noise from propeller-driven aircraft is a combination of two main noise sources, the propeller and the powerplant. For larger, higher horsepower (and hence louder) aircraft, propeller noise is the more important noise source and generally exceeds the noise from the powerplant with respect to its absolute level and disturbing effects, while with smaller airplanes (typically below 300 hp) powerplant noise can and often does dominate total aircraft noise. For the Cessna 150 test airplane used in this study, the maximum takeoff weight is 1600 lb, and the takeoff length to clear a 50-foot object is 1385 feet. Thereafter, the rate of climb is 670 ft/min at an indicated airspeed of 76 mph. This places FAR Part 36 noise limits of 73 dB_A at a height of 736 feet over the recording device.

Total propeller noise is composed of a rotational component, a thrust component, and vortex noise. Rotational and thrust noise is composed of a series of harmonics of the blade passing frequency, equal to the number of blades times the propeller revolutions per minute (rpm). The sound pressure level distribution is typically highest for the fundamental blade passing frequency and is subsequently lower for each higher harmonic until the broadband vortex noise dominates at the highest frequencies. The level of rotational noise generated at the fundamental frequency and the total noise level of the propeller can be estimated from the propeller and engine characteristics (e.g. propeller disk diameter, number of blades, blade cross-section, blade rpm, engine horsepower).

The Cessna 150 has a propeller fundamental blade passing frequency of 84 Hz (2500 rpm/60 × 2 blades). The propeller noise can be estimated from the propeller disk area, engine horsepower, and propeller tip speed [1]. For the 69" diameter propeller on the Cessna 150, the propeller tip speed is 760 ft/sec, or 0.7 Mach. At the measurement location (5 feet away at a 60° angle from the fuselage), the overall propeller noise level is estimated to be 104-106 dB, the 84-Hz tone 102-104 dB, and the second harmonic (168 Hz) 97-99 dB. Using an alternate method for estimating propeller noise [2] gives an overall propeller noise level of 136 dB in the plane of the propeller, corrected to a value of 110 dB at the measurement location with a value at the fundamental frequency of 108 dB. These values represent total sound output and are not weighted for human noise sensitivity.

The noise from reciprocating engines, meanwhile, originates from the periodic expulsion of hot combustion gases through the exhaust. Noise radiation from other parts of the engine is not appreciable and will not be noticed (except possibly as vibrations inside the aircraft cabin) unless extremely quiet mufflers and propellers are utilized. The source of exhaust noise is constituted by the periodic volume flow, which, to a first approximation, radiates from the exhaust in all directions as a monopole sound source. The lowest frequency of the exhaust noise spectrum is given by the number of exhaust discharges per cylinder per second, which normally corresponds to the firing frequency.

The engine noise produced by the Continental O-200 engine on the Cessna 150 is generated by a 200-in^3 displacement, four-stroke, four-cylinder engine operating at 2500 rpm at maximum power. At 2500 rpm, or 42 revolutions per second, each cylinder produces 21 exhaust pulses every second, for a firing frequency of 84 Hz. This is the fundamental exhaust frequency. From theoretical estimations, the total sound output at the engine exhaust is predicted to be 135 dB, and 132 dB at the fundamental firing frequency. Correcting for the 5-ft distance from the exhaust opening where measurements are taken during testing gives an expected overall exhaust noise level of 121 dB at the fundamental frequency of 118 dB for the unmuffled engine, with an expected accuracy of ±5 dB.

2.2 Noise Reduction Approaches

The two major noise sources, propeller and engine noise, can be reduced through design modifications and the use of noise filters/absorbers (mufflers). To reduce propeller noise, smaller, slower tip speed propellers with a greater number of blades are required. The general industry trend has been to change from two-bladed to three-bladed propellers, and four-bladed propellers may be found on many newer airplanes. However, new propellers may be prohibitively expensive for most owners, as a typical three- or four-bladed constant-speed propeller upgrade costs $3000-6000 (exceeding EPA estimates).

Two basic design approaches have been used for acoustic (i.e., noise) attenuation devices, or mufflers: reactive and dissipative. In its most basic form, a reactive muffler uses the reactance of air (i.e., an "air spring") interacting with geometric elements to create destructive interference and wave cancellation, thus reducing noise levels. Reactive mufflers also typically contain reflective elements, which direct sound waves back toward their source. Conversely, dissipative mufflers use flow resistance in the form of baffles or linings to dissipate acoustic energy through airflow frictional forces.

Reactive muffler elements include expansion chambers, side-branch resonators, bends, expansions, contractions, and terminations. The most important reactive elements in terms of muffler design and tuning are expansion chambers and side-branch resonators. These items must be sized for each frequency, and their design requires knowledge of the desired minimum attenuation at each frequency, the maximum acceptable pressure drop at the design flow rate, and the geometric and weight constraints of the overall muffler system. In general, attenuation of low-frequency noise requires long muffler lengths and/or large muffler volumes. Reactive muffler elements are well-suited to low-frequency (<500 Hz) noise attenuation, but generally perform less well at higher frequencies. Reactive designs also have very sharp frequency dependencies and must be carefully tuned for peak performance. The frequency dependency of a side-branch resonator, which is a typical example of a reactive muffler design, is shown in Figure 1.

For higher frequency noise, dissipative muffler designs are the most applicable. Key dissipative elements include acoustic linings, lined bends, expansion chambers, and plenum chambers. Dissipative designs generally have a lower frequency cutoff limit with increasing noise attenuation occurring at higher frequencies. The frequency dependency of a typical dissipative muffler is shown in Figure 2. The geometry (e.g. length and diameter) and absorptive characteristics (e.g. thickness, flow resistance, reactance) of dissipative mufflers are critical to their performance.

Aircraft reciprocating engine muffler design presents serious difficulties in applying current reactive and dissipative design elements. Current automotive two- and three-pass type mufflers are ideally suited to the acoustic requirements, but generate 6-15 inHg of backpressure, well above the allowable limits for aircraft engines. On the other hand, straight-through type mufflers using side-branch resonators must be excessively long and have large volumes, and are therefore unsuitable based on geometric, weight, and induced drag considerations, although their acoustic and mechanical performance (pressure drop) are most suitable. Conventional dissipative designs, while meeting weight, size, and pressure drop considerations, do not meet acoustic requirements because of the importance of low frequencies.

Of prime importance to dissipative muffler design is the availability of the correct dissipative material. The mufflers designed and fabricated in this project required a unique material capable of resisting the considerable mechanical forces induced at the elevated temperatures common to muffler operation. Conventional absorptive/dissipative materials (e.g. glasspacks and felts) are relatively weak and friable, leading to rapid mechanical degradation when placed in high-dB flow streams. In addition to the required mechanical performance, an effective absorber/liner material must also be tailorable in terms of acoustic properties and present relatively low resistance to flow. Open-cell foams constitute such a unique dissipative material, specifically silicon carbide (SiC) foam manufactured by chemical vapor deposition (CVD). This material, with its high porosity (leading to low flow resistance, or backpressure) and excellent high temperature corrosion resistance, was ideal for construction of the innovative mufflers designed in this project.

2.3 Muffler Design

The unsuitability of existing muffler designs can be resolved only through major aircraft modification (e.g. changing engine frequency and using reduction gears, reconfiguring the engine cowl and entire exhaust system) or innovative muffler designs. The design approach taken in the current project was to utilize dissipative-type designs but allow for plane-wave attenuation (low-frequency wave propagation is through plane waves, which are not usually affected by the dissipative lining) by forcing a significant part of the flow to pass through the dissipative/liner material. These designs involve the use of lined expansion chambers with small percentages of open area (the majority of the cross-sectional area is taken up by the liner), or resistive baffles placed normal to the flow rather than their current placement parallel to the flow. These two muffler design concepts are illustrated in Figure 3.

This new type of muffler design introduces considerable complexity to the design calculations, since all components of the muffler have resistive and reactive elements associated with them, as well as direct resistances/attenuations similar to structural noise reduction systems. Great emphasis must also be placed on mechanical performance, and the acoustic and mechanical performance calculations must include partitions of the flow (percentage passing through dissipative elements). However, the current work clearly demonstrated that acceptable mechanical, acoustic, and geometric/weight performance requirements could be met with this type of design.

3. EXPERIMENTAL APPROACH

The specific technical objective of this project was to develop a complete, improved general aviation aircraft exhaust system meeting the following requirements:

- Noise level: reduced by a minimum of 10 dB_A, and up to 20 dB_A, compared to conventional straight-pipe exhaust systems.
- Overall size: sufficiently compact to fit under engine cowlings with minimal modification.
- Overall weight: minimized sufficiently so as not to exceed 125% of the weight of conventional exhaust systems.
- Cost: \$850-3000 per complete muffler system, or within 150% of the cost of conventional exhaust systems, including \$200-900 of SiC foam material per system (based on a foam volume of 75-200 in^3).
- Performance: no more than 2 inHg backpressure.

Ultramet developed design data for specifying the open-cell SiC foam broadband noise absorber, then designed, fabricated, and tested various mufflers based on this material. Ground and flight testing were performed by AvSpec Corp. (Rocklin, CA), while the metal work required to fabricate completed mufflers was performed by Knisley Welding (Loomis, CA).

Mufflers with various configurations of exhaust gas flow through the SiC foam material were fabricated and tested to determine the insertion loss, change in sound pressure level, noise reduction as a function of frequency, and sound absorption resulting from the use of SiC foam of various pore sizes, porosities, and densities. Ground testing of SiC foam-based muffler systems was accomplished using a sound wave generator/speaker system for initial screening, a privately owned Cessna 150 aircraft and a NASA-owned YO-3A aircraft for prototype muffler testing, and a dynamometer-mounted Continental O-200 engine for testing in the absence of propeller noise. Flight testing was performed using a SiC foam muffler prototype mounted on a Cessna 150 aircraft equipped with a Continental O-200 engine.

The experimental approach for project performance was divided into six major tasks, detailed below:

- Baseline testing
- Evaluation of commercial mufflers
- Analytical noise prediction
- Prototype muffler development and testing
- Catalytic converter evaluation
- Flight testing.

3.1 Baseline Testing

Baseline data, needed to evaluate the effects of modifications made to the original equipment manufacturer (OEM) exhaust system, were collected from the baseline aircraft, AvSpec's Cessna 150. The data collected included engine cooling efficiency, engine temperature, exhaust backpressure, interior noise levels inside the cockpit at takeoff and during flight, and exterior noise surrounding the airplane.

3.1.1 Engine Cooling

Four cylinder-head temperature transducers, an oil temperature transducer, an outside air temperature transducer, a digital tachometer, a pressure transducer, and an altitude transducer were instrumented on the baseline aircraft to record engine temperature and exhaust backpressure. Measurements of baseline exhaust performance under flight conditions included climb cooling and carburetor heat. This test was performed in accordance with FAR test procedures (FAR 23.1047 for climb cooling and FAR 23.1093 for carburetor heat).

3.1.2 Interior Noise

Interior noise measurements were performed during ground run-up, takeoff/climb, low power flight (cruise), maximum power flight, and power-off descent (i.e., a shallow dive with the engine shut down and the propeller free-wheeling). The aircraft was equipped with instrumentation to accurately measure propeller revolutions and interior cockpit noise (in decibels, A-weighted). Two microphones were installed inside the cockpit, one between and one aft of the two pilot seats.

3.1.3 External Noise

The external noise mapping of the stock muffler system was performed at 2250 rpm using a four-bladed cooling club. Noise measurements were performed in 15° angle increments (from 0 to 90°), at one, two, and four feet off the ground, and at 2.5, 5, 10, 15, and 20 feet away from the exhaust location. A total of 30 of these data points were mapped.

3.1.4 Stock Muffler Characterization

Characterization of the Continental O-200 stock muffler performance was performed to measure sound pressure levels before and after the exhaust cavity. As shown in Figures 4A-C, three liquid-cooled pressure transducers were mounted on the stock Cessna 150 exhaust system, one in the tailpipe downstream of the muffler (1" below the exhaust flange on the right side of the aircraft), the other two at the risers of cylinders #1 and #3. The sound pressure level was measured in one-eighth octave bands from 25 to 4000 Hz at these locations. The data were collected at three engine speeds (1800, 2100, and 2400 rpm) and were reduced in the form of frequency vs. relative sound pressure level distributions. The data acquisition system was set to acquire 25,000 samples per second.

3.2 Commercial Muffler Evaluation

Off-the-shelf automobile exhaust systems were evaluated using the baseline Cessna 150 aircraft. The evaluation included measurements of sound pressure level distributions at the same mapping locations used for the baseline noise measurements, also using the four-bladed cooling club. The commercial mufflers were connected to the tailpipes of the stock mufflers, one on each side of the aircraft. The commercial muffler test setup is shown in Figure 5. Six pairs of commercial automobile mufflers were evaluated:

- 5" diameter × 12" long Genie Turbo cylindrical mufflers
- 4" diameter × 14" long B&B Fabrication Tri-Flow Ceramic cylindrical mufflers with composite outer skins
- 6" diameter × 12" long Borla Performance cylindrical mufflers
- 6" diameter × 16" long Borla Performance cylindrical mufflers
- 13" long Borla Performance elliptical mufflers
- 17" long SuperTrap mufflers with external baffle plates capable of extending the overall length by 1-4".

All muffler pairs were equipped with 2" diameter × 2" long inlet and outlet tailpipes.

3.3 Analytical Noise Prediction

Two computer programs, ANSYS and SYSNOISE, were used as predictive tools to model muffler noise attenuation capabilities. ANSYS was used to generate finite element models of the various muffler designs of interest, which were then loaded into SYSNOISE for acoustic performance analysis. SYSNOISE predicts the radiation, reflection, diffraction, and transmission of sound waves and the structural vibrations induced by the loading effects of the acoustic fluid onto the structure, and calculates a wide variety of results, such as sound pressures, acoustic intensities, vibro-acoustic sensitivities, normal modes, and structural deflections. Due to budgetary constraints, the version of SYSNOISE used in this project was only capable of calculating sound pressure levels and transmission losses.

3.4 Prototype Muffler Development and Testing

3.4.1 Muffler Design and Fabrication

All of the more than 30 prototype muffler configurations fabricated in this project were wrapped with 0.125" steel sheet to form 4" inner diameter (ID) × 12" (or 15") long cans with 2" outer diameter (OD) × 2" long inlet and outlet tailpipes to conform to general aviation aircraft under-cowling space limitations. The configurations of the ceramic foam contained within the steel cans were varied to screen the acoustic suppression effectiveness of the material.

The ceramic foam used in all muffler designs was open-cell SiC foam, which consists of a SiC ceramic coating applied by CVD onto a reticulated vitreous carbon (RVC) foam substrate derived from polyurethane foam. SiC foam can be produced in bulk densities ranging from 0.15 to 0.65 g/cm^3, pore sizes ranging from 3 to 100 pores per linear inch (ppi), and porosities ranging from 65 to 92%. SiC foams have demonstrated excellent resistance to high-frequency (up to 170 dB) vibration and high temperature flow environments, and their tailorability makes them uniquely suited to this application. SiC foam mechanical and thermal properties have been thoroughly characterized through numerous other research efforts. To minimize cost and weight, all SiC foam fabricated in this project was 100 ppi with ≈10% SiC coating (bulk density of 0.32 g/cm^3). Preliminary flow and acoustic property relationships as functions of foam pore size and density had been characterized in the Phase I project [3], and those data were used as inputs in the analytical programs.

3.4.2 Insertion Loss Measurement

Measurements of insertion loss (i.e., the difference in sound pressure level between two points) were performed to inexpensively screen the various muffler configurations for further ground testing. As illustrated in Figure 6, the noise source used for this testing was a sine wave generator coupled to a wood-enclosed speaker box, which was covered with an acoustic blanket to prevent intrusion of exterior noise. Handheld dB meters were placed at the locations indicated. Sound pressure levels were measured as a function of frequency up to 3000 Hz. Insertion loss between the muffler inlet and outlet was of particular interest, as this expresses the direct acoustic performance of the SiC foam inside the expansion chamber. In this case, insertion loss was defined as the difference between $\Delta SPL_{exit\text{-}box}$ values for the tested muffler configuration and a conventional straight-pipe configuration, where $\Delta SPL_{exit\text{-}box}$ is the difference between the sound pressure level at the exit of the muffler and the noise-producing speaker box at the entrance of the muffler. A 2" ID × 11.5" long straight pipe and a 4" ID × 11.5" long hollow expansion chamber were tested as the baseline muffler designs.

3.4.3 Ground Testing

To establish correlations and confirm the bench test data, ten promising muffler configurations were chosen for ground testing. Instead of the Cessna 150 aircraft, ground testing was performed using the NASA Ames Research Center (ARC) YO-3A research aircraft, based first at ARC and subsequently at NASA Dryden Flight Research Center (DFRC), because data from previous testing using the Cessna had revealed the difficulty of separating engine noise spectra from propeller noise spectra for that aircraft. The YO-3A, a retired military aircraft purchased and modified for acoustic testing by NASA ARC, has two features designed to reduce noise output: a slow-turning, low-noise propeller with low tip speed, and a long straight-pipe muffler mounted under a prominent starboard cowling, running the length of the fuselage (the aircraft could also be equipped with a short pipe). These two features make this aircraft uniquely suited to direct measurement of engine and exhaust noise. The YO-3A, shown in Figures 7A-D, is equipped with a Continental O-360 engine and a three-bladed propeller with 3:1 belt reduction. Because the data to be generated from this testing were of interest to NASA, the aircraft, along with the ground crew and additional instrumentation needed for testing, were provided at no cost.

Before testing the newly developed prototype mufflers, baseline YO-3A noise measurements were made as a reference. All baseline measurements were performed at an engine speed of 2100 rpm, with the engine cowling both installed and removed, and using both the long and short exhaust pipes. This allowed direct comparison of the noise spectra of the short and long exhaust pipes (the exhaust exit of the long pipe is several feet aft of the short pipe exit). Handheld dB meters were used to record the overall average sound pressure level distribution, while data at certain locations were recorded using a data acquisition system to generate frequency spectra. Backpressure was also recorded during each test by recording the difference between the static exhaust pressure before engine startup and at 2400 rpm. Figure 8 shows a diagram of the sound mapping arcs originating from the YO-3A stock short-pipe exhaust, as well as the individual mapping locations at which noise measurements were taken.

The ten muffler configurations that showed the most promise during bench testing were welded in 4" OD × 11" long straight stainless-steel expansion chambers with 2.5" diameter inlets and outlets. These prototype mufflers had the following specifications:

- Prototype muffler #1: a 4" OD × 11" long straight pipe containing a 4" OD × 2" ID × 10.5" long liner of 100-ppi, 10% dense SiC foam, illustrated in Figure 9.
- Prototype muffler #2: same as #1 except for the SiC foam density, which was 20%.
- Prototype muffler #3: a 4" OD × 11" long straight pipe containing perforated 100-ppi, 10 and 20% dense SiC foam plates and baffles of various thicknesses and inner diameters, illustrated in Figure 10.
- Prototype muffler #4: a 5" OD straight pipe with a 21" long offset outlet containing a 100-ppi, 10% dense SiC foam liner at its inlet and a swirled, 20% perforated internal steel sheet, illustrated in Figure 11. This muffler weighed ≈9 lb and had not been tested for insertion loss.
- Prototype muffler #5: same as #1 except for length (15.5" vs. 11"), illustrated in Figure 12. This prototype was developed to evaluate the effect of duct length on noise damping/attenuation.
- Prototype muffler #6: a 4" OD × 11" long straight pipe containing 4" OD × 1.75" ID × 1" thick, 100-ppi, 10% dense SiC foam baffles with offset core holes alternating with thin 10-ppi, 10% SiC foam spacer rings, illustrated in Figure 13. The baffles were stacked such that the core holes were 180° apart. This prototype was developed to generate a longer path for sound to travel, which improves noise attenuation.
- Prototype muffler #7: same as #6 except for length (17.5" vs. 11"), illustrated in Figure 14.
- Prototype muffler #8: a 4" OD × 11" long straight pipe containing a 4" OD, 40-ppi, 10% dense SiC foam cone fitted partially inside a 4" OD × 3.5" ID × 9" long, 100-ppi, 10% dense SiC foam cylinder, illustrated in Figure 15.
- Prototype muffler #9: same as #5 except for a 0.002" perforated metallic sheet enclosing the OD of the SiC foam liner.
- Prototype muffler #10: a 4" OD × 11.5" long straight pipe containing three segmented expansion chambers of 100-ppi, 10% dense SiC foam of varying inner diameters and thicknesses and two 40-50% perforated plates, illustrated in Figure 16.

All metal work was performed by Knisley Welding. A prototype muffler installed on the YO-3A aircraft is shown in Figures 17A-B. A steel flange was used to mount the exit of the tested mufflers to the aircraft wing to keep them from vibrating during testing. All measurements were taken at an engine speed of 2100 rpm, with the cowling on and with the aircraft positioned on the grid used previously to conduct baseline noise measurements using the stock short-pipe muffler (see Figure 8). All sound pressure level data were measured in dB_A, using a data acquisition system for locations #1, 6, and 10 and handheld dB meters for all other locations.

3.4.4 Dynamometer Testing

A universal dynamometer was constructed to test promising prototype mufflers without propeller noise interference. Figure 18 shows the final dynamometer assembly without the acoustic chamber or the engine cooling duct. The dynamometer assembly, although specifically equipped with the Continental O-200 engine, was designed to be universally adaptable to any engine. The assembly was designed for convenient relocation to an alternate test site, if desired.

The water brake, shown in Figure 19, was adjustable along the drive shaft axis to accommodate mounting of various-sized engines to the test stand. The water brake inlet was connected to an ordinary water faucet, while the outlet drained into large barrels. The instrumentation panel, shown in Figure 20, consisted of a series of gauges to measure water pressure, water temperature, engine backpressure, engine temperature, and engine speed. Figure 21 shows the cooling system for the engine. A hood was fitted directly on the engine, and a flexible duct connected the hood to a cooling fan, which was placed on a rolling cart to make the cooling assembly easily portable.

An acoustic chamber measuring ≈24" diameter × 36" long, shown in Figure 22, was initially connected to the engine exhaust pipe with a test muffler suspended in its center. However, initial testing indicated that the acoustic chamber itself acted as an expansion chamber, attenuating the majority of incoming noise; for this reason, the acoustic chamber was eliminated.

3.5 Catalytic Converter Evaluation

Perforated metal and catalyst-coated SiC foam tubes were procured for evaluation of the effectiveness of the muffler designs in reducing emissions. Stock aircraft engine emissions and emissions from the same engine equipped with a catalyst-coated SiC foam muffler were measured, then compared using the dynamometer. Based on the results of this testing, the optimal muffler configuration was downselected for on-engine testing.

Straight, 45-ppi SiC foam acoustic flow-through liners were coated with catalyst compounds, then tested on a Continental O-200 piston-powered four-cylinder engine producing 100 hp at 2750 rpm (using low-lead, 100-octane fuel). The engine was mounted on a dynamometer test stand, which was used to apply load. The flow-through converter/acoustic liners were mounted approximately six feet from the engine manifold. Emissions were measured using a five-gas analyzer--carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x), and oxygen (O_2)--both with and without the converter attached, at engine speeds ranging from 1000 to 2750 rpm. Time to lightoff was not measured.

3.6 Flight Testing

Mufflers consisting of SiC foam liners canned within airworthy steel tubes were fabricated and installed under the engine cowling of a Cessna 150 aircraft equipped with a Continental O-200 engine (one for each side of the engine). Figures 23A-B show the as-fabricated mufflers before installation, while Figures 24A-B show the mufflers mounted to the engine. Installation proved simple, with the mufflers fitting entirely beneath the aircraft's existing cowling. Flight testing was conducted at Lincoln Regional Airport (Lincoln, CA), the runway configuration of which is shown in Figure 25. The noise measurement instrumentation used in flight testing is shown in Figures 26A-B. Both takeoff (flight profile #1) and low-approach (flight profile #2) noise levels were measured on a dB_A scale using a FAA-certified BBN model 614 noise monitor, and also using a handheld dB_A meter. The pilot also recorded observations regarding the performance of the aircraft equipped with SiC foam-based mufflers during flight testing.

Flight profile #1 comprised a standard takeoff configuration, with climbout performed at 70-mph indicated airspeed. Maximum power was used throughout the climb. The climb was maintained until the aircraft passed over the measurement site. Flight profile #2 comprised a low approach (flyover) over the measurement site conducted at an engine speed of 2200 rpm and an indicated altitude of 620 feet, with the barometric pressure set per the airport's Automated Weather Observing System (AWOS). During both flight profiles, the pilot recorded AWOS data, including altitude, barometric pressure, wind speed and direction, temperature, and time, at the moment the aircraft passed over the measurement site.

4. RESULTS AND DISCUSSION

4.1 Baseline Testing

4.1.1 Engine Cooling

All data generated during climb cooling showed that the Cessna 150 aircraft's Continental O-200 engine met all certification requirements and that the maximum measured temperatures (corrected for 100°F ambient temperature) were below the maximum acceptable temperature of 240°F specified in the Continental O-200 Type Certificate Data Sheet. Data generated from the available carburetor heat showed that the Cessna exhaust heat exchanger provided the required heat to the carburetor as prescribed in the FAR procedures. The accessory compartment heat and available cabin heat were also well within the normal limits. These data provided a baseline for acceptable temperature ranges for engine compartment components and available carburetor heat.

4.1.2 Interior Noise

A summary of all interior noise levels generated from the various flights and conditions is given in Table I. According to the data, the highest noise levels were generated during takeoff (93.9 dB_A) and during cruise flight at the lowest engine speed of 2050 rpm (93.4 dB_A). This implies that the higher noise levels are not due to wind noise.

4.1.3 External Noise

The non-calibrated external noise level distribution measured from the Cessna 150 stock muffler is shown in Figure 27. Only the noise levels measured at one and four feet off the ground are shown, indicated as L and H respectively. Noise level measurements at locations #6, 16, 17, 22, 26, and 27 on the 2.5-ft and 5-ft arcs could not be made due to interference from the aircraft structure. From the measured data, minimal noise level differences are noted between the 1-ft and 4-ft heights. Higher noise levels appear to have been generated within the 10-ft arc and between the 30° and 75° angle locations (directly behind the exhaust tailpipe). A maximum noise level of 133.5 dB_A (corrected) was measured on the 2.5-ft arc at a 30° angle.

4.1.4 Stock Muffler Characterization

Figure 28 shows the overall relative sound pressure level inside the Continental O-200 stock tailpipe as a function of frequency. The relative pressure level was expressed as $1e^{-x}$, with the exponent x representing the number of 10-dB steps below a fixed reference value. $1e^{0}$ was used as the reference, with $1e^{-1}$ corresponding to 10 dB lower than the reference, $1e^{-2}$ corresponding to 20 dB lower than the reference, etc. As seen, the majority of overall sound pressure was produced at frequencies ranging from 0 to 600 Hz, after which sound pressure remained at a uniform, substantially reduced level all the way up to 4000 Hz. The sound pressure levels from the three transducers are compared in Figure 29, which shows their similarity with one another. The characteristic peak sound pressure level of each cylinder, as well as that of the tailpipe, occurred at ≈15-20 Hz (a total of ≈60-80 Hz for a four-cylinder engine), as shown in Figures

30-32. Table II summarizes the fraction of total sound pressure measured over various frequency ranges. Approximately 95% of the total sound pressure was generated in the 15-90 Hz range, with 70% generated in the 15-30 Hz range.

The data obtained from stock muffler characterization implies that the noise output of the Continental O-200 engine must be reduced primarily in the 15-90 Hz range, with specific emphasis given to the 15-30 Hz range, which alone accounted for 70% of the noise output.

4.2 Commercial Muffler Evaluation

The average sound pressure levels measured from all the commercial mufflers at all mapping locations are compared to the stock Cessna 150 muffler sound pressure levels in Table III, while the backpressures induced by the commercial mufflers are given in Table IV. Minimal changes in sound pressure level were measured between the stock mufflers and the commercial mufflers.

In general, the glasspack-type mufflers (e.g. SuperTrap) reduced noise over a broad range of frequencies (1500-2500 Hz), while the expansion chamber-type mufflers (e.g. Genie) removed one or two sound peaks in the 100-400 Hz range. This implies that the mufflers performed as desired, that engine exhaust noise is the major noise contributor at frequencies below 400 Hz and above 1500 Hz, and that engine noise is the dominant overall noise contributor. The data appear to confirm the Phase I results, indicating that tuning of the specific muffler system and incorporation of broadband noise reduction methods is required to significantly reduce the overall sound pressure level.

4.3 Analytical Noise Prediction

A representative finite element model of a quarter-section of a baseline 4" OD × 10" long expansion chamber resonator (with no SiC foam liner) with 2" diameter × 2" long inlet and outlet pipes (total length 14") is shown in Figure 33. The model consists of 1312 elements and 6397 nodes, with an expansion ratio of $m=S_2/S_1$, where S_2 is the cross-sectional area of the expansion chamber and S_1 is the cross-sectional area of the inlet pipe. The sound pressure distribution and transmission loss inside the baseline expansion chamber were computed using a finite element model direct response approach and are shown in Figures 34 and 35 respectively.

The transmission loss curve of the baseline expansion chamber with an expansion ratio of m=4 containing no sound-absorbing liner or materials had a resonance frequency of 700 Hz, with a maximum loss of 8.4 dB occurring at 300 Hz. These data agree quite well with theoretical data derived from plane-wave theory [1]. The transmission losses for a single expansion chamber as a function of expansion chamber length are shown in Figure 36 for several values of m, as calculated from plane-wave theory. The curve for m=4 shows a resonance frequency of ≈700 Hz, with a maximum loss of 7.8 dB occurring at 340 Hz.

The baseline model was then modified to include a 0.5" thick SiC foam liner, as shown in Figure 37. The acoustic performance was measured in terms of transmission loss as a function of frequency and porous material characteristics such as ppi, thickness, structural factor, and flow resistivity. The SiC foam characteristics used in the acoustic modeling are listed in Table V. Flow resistivities input into the SYSNOISE program were taken from predicted values at the speed of sound (340 m/sec) based on linear relationships derived from various flow rate measurements.

From the propagation constant equation [1], the structural factor k was determined from a first-order approximation relationship as being:

$$k = 1 + 4.55(1-Y)$$

where Y is the material porosity.

A 1" thick lined duct was also analyzed, as shown in Figure 38. The effects of material thickness, flow resistivity (pore size), and porosity on transmission loss were compared to the baseline measurements (no porous acoustic materials present) and are shown in Figures 39-41 respectively. It is apparent that the noise attenuation resulting from a lined duct is primarily dependent on the flow resistivity (and thus porosity) of the porous material. It is also apparent that the acoustic performance of the SiC foams is not as effective in lower frequency regions (<600 Hz) as it is in higher frequency regions. Also, the presence of a lined duct appears to shift the resonance frequencies by ≈100 Hz to the left compared to the unlined expansion chamber. Analysis of the various combinations of material characteristics suggests that a 1" thick liner of 100-ppi, 20% dense SiC foam would induce the most effective transmission loss, as shown in Figure 42. In other words, the 1" wall thickness (vs. 0.5") is necessary to obtain a total liner cross-sectional area equal to the cross-sectional area of free air passage, thus producing a significant loss.

Four iterations of 1" thick parallel foam baffles were acoustically analyzed, including solid baffles, 1" diameter donut baffles, 2" diameter donut baffles, and 1" diameter donut baffles with 0.5" diameter holes. These four models and their associated transmission loss curves are shown in Figures 43-50 respectively. The transmission loss curves from all four models showed very similar acoustic behavior, in that the acoustic performance of each model was primarily dependent on material characteristics and rather independent of baffle geometry.

4.4 Prototype Muffler Development and Testing

4.4.1 Insertion Loss Measurement

Individual sound pressure levels generated from the various muffler configurations using the insertion loss measurement apparatus shown in Figure 6 are summarized in Appendix A. Representative individual sound pressure level spectra of untreated and treated mufflers are shown in Figures 51-55. An average insertion loss of 5-10 dB was measured between the duct inlets and outlets, with an expansion ratio of 4 between the straight pipe and the hollow expansion chamber. All far-field 0° and 30° spectra showed similar noise attenuation patterns, suggesting consistent spherical spreading. Significant noise attenuation was observed for all treated mufflers. Prototype muffler #5, the lined expansion chamber with a perforated skin covering the outer diameter of a SiC foam cylinder, had the greatest insertion loss (up to 35 dB). The insertion loss increased with increasing frequency, which agreed well with the results of SYSNOISE acoustic modeling. However, inconsistent with analytical predictions, there was significant noise attenuation between the inlet and outlet of unit #5 in lower frequency regions; an insertion loss of ≈28 dB was recorded at 40 Hz.

In general, the static bench test results indicated that higher insertion loss was generated at frequencies of ≈800 Hz for all muffler configurations. This implies that the SiC foams absorbed noise more effectively in higher frequency regions. Insertion losses of up to 30 dB were measured at ≈800 Hz, while losses of up to 10 dB were measured at <800 Hz. Higher sound pressure levels (i.e., lower insertion losses) were measured at the muffler outlets when air was injected at the inlets, most likely due to turbulence caused by the air flow. SiC foam density (10% vs. 20%) had little apparent effect on noise attenuation. Baffled muffler configurations showed less insertion loss than the lined configurations, while the cone configuration was one of the least effective configurations tested, even at high frequencies (>1000 Hz). The effect of varying muffler duct length is illustrated in Figure 56, which shows a plot of sound pressure level as a function of frequency at the outlets and exits of two liner configurations identical except for length (11" vs. 15" long). Little or no effect is evident, suggesting that any noise reduction improvement resulting from longer liner length may not be sufficient to justify the added muffler weight.

Promising muffler configurations were downselected for ground testing and were assembled in appropriate canning representative of actual mufflers retrofittable under minimally modified aircraft cowlings.

4.4.2 Ground Testing

A backpressure of 0.7 inHg was recorded from the baseline stock short-pipe muffler attached to the NASA YO-3A aircraft used for ground testing. When the exhaust was reconfigured to use the stock long-pipe muffler, 1.2 inHg maximum backpressure was measured, an increase of 0.5 inHg, which is still far below the maximum allowable limit of 2 inHg as given by the Type Certificate Data Sheet. Data from the handheld dB meters, which represent overall average sound pressure levels for each test, are summarized in Figures 57-59. A noise reduction of 1-2 dB was consistently recorded with the cowling installed compared to removed, and an average noise reduction of 4 dB was recorded using the long pipe compared to the short pipe.

Theoretically, for a six-cylinder engine operating at 2100 rpm, the first fundamental frequency should be 105 Hz, while a three-bladed propeller should have a fundamental frequency at 35 Hz. These fundamental frequencies can be clearly differentiated on all sound pressure level vs. frequency spectra generated from the baseline short pipe test data, as seen in the most representative spectra shown in Figures 60A-C. The effect of the long pipe on sound pressure level distribution compared to the short pipe can be seen clearly in Figures 61A-B. A 14-dB noise reduction, from 77 dB to 63 dB, was observed at the first fundamental engine frequency using the long pipe compared to the short pipe. These baseline data indicated that the YO-3A aircraft was suitable for ground testing of the SiC foam-based mufflers.

Data recorded from the handheld dB meters are given in Table VI, along with data generated from the baseline long-pipe muffler configuration. Backpressures measured for all muffler configurations are also listed in Table VI. Prototype muffler #3, which contained the combination of perforated plates and baffles, produced excessive backpressure (≥5 inHg), so no data were recorded for it.

The backpressures of prototype mufflers #5-10 mounted on both the Cessna 150 and NASA YO-3A aircraft were also measured; the resultant data are given in Table VII. Much lower backpressures were measured for the mufflers mounted on the Cessna (which has a four-cylinder engine) than for the YO-3A (which has a six-cylinder engine). All prototype mufflers induced backpressures far below the maximum allowable (2 inHg) on the Cessna.

- Baseline measurements: Baseline noise was measured using the stock short-pipe muffler. Figures 62A-B show the test setup with and without the muffler attached. The sound pressure levels were measured using the data acquisition system at locations #1, 6, and 10, as shown in Figure 8. Due to some interference from the aircraft wing, the sound pressure level spectra recorded at locations #6 and #10 were not as representative as those recorded at location #1. Representative sound pressure levels at major frequencies measured at location #1 are given in Table VIII. The highest average sound pressure level (recorded by handheld dB meters) was 106 dB_A at location #6 (immediately behind the exhaust pipe), while the lowest, 90 dB_A, was recorded on the 30-ft arc. The data from the sound pressure level spectra showed the highest sound pressure level, 99 dB_A, occurred at 105 Hz at location #1.

- Prototype mufflers #1, #2, and #4: These mufflers demonstrated equivalent acoustic performance. Noise levels ≈3-4 dB_A lower on the 0° axis and 1-2 dB_A lower on the 30° and 60° axes compared to the baseline short pipe were recorded using handheld dB meters for these units. An increase in backpressure of only 0.2 inHg (from 0.7" to 0.9 inHg) was measured for the lined mufflers (units #1 and #2), implying that these are free-flow designs, while an increase of 0.7 inHg was measured for unit #4, the combination of foam and the swirled, perforated metal sheet. Units #1 and #2, which were lined with 100-ppi, 10% and 20% dense SiC foam respectively, generated similar noise levels and backpressures, suggesting that foam density had no effect on noise attenuation. This confirmed the data obtained from bench testing. Units #1 and #2 demonstrated acoustic performance equivalent to the baseline YO-3A long-pipe muffler (with the aircraft repositioned for comparison to the short-pipe configuration) with less backpressure (0.9" vs. 1.2 inHg), yet it weighed only 4.5 lb (vs. 150 lb for the long pipe).
- Prototype muffler #5: This muffler, consisting of a straight 4" OD × 15" long tube lined with a 4" OD × 2" ID × 15" long, 100-ppi, 10% dense SiC foam flow-through cylinder, weighed 4.8 lb and duplicated prototype #1 except for length (15" vs. 11"). It was developed to evaluate the effect of duct length on noise attenuation. Figures 63 and 64 are sound pressure level spectra recorded for prototype mufflers #1 and #5 respectively, measured at location #1. Similar noise attenuation trends were observed for both units, except that the sound pressure level was lower below 200 Hz for the 15" duct length (unit #5) relative to the 11" duct length (unit #1). All the flow-through duct designs (configurations #1-5) were shown to consistently reduce the sound pressure level (up to 15 dB_A lower at 810 Hz) above 600 Hz. Below 600 Hz, this design generated a higher sound pressure level (up to 5.5 dB_A higher at 185 Hz) relative to an unmuffled engine. A minimal increase in backpressure (from 0.75 to 1.05 inHg) was measured for this muffler as mounted on the YO-3A aircraft, while a backpressure decrease (from 0.9 to 0.7 inHg) was measured for the muffler as mounted on the Cessna 150 aircraft. Given its light weight and minimal backpressure, this design constitutes a viable broadband noise absorber for the engines tested, yielding excellent noise attenuation above 600 Hz.
- Prototype muffler #6: This muffler consisted of a straight 15" long tube containing a stack of 4" OD × 1.75" ID × 1" thick, 100-ppi, 10% dense SiC foam baffles with offset core holes alternating with thin, 10-ppi, 10% SiC foam spacer rings. The design is shown schematically in Figure 13. The baffles were stacked such that the core holes were 180° apart. This design was developed to provide a longer path for the sound to travel. Mounted on the YO-3A aircraft, this muffler induced 3.8 inHg of backpressure (almost twice the maximum allowable), compared to only 1.1 inHg when mounted on the Cessna 150. Consistent sound pressure level reduction was measured at frequencies ranging from 75 to 2500 Hz. Of all the prototypes tested, unit #6 was one of the most effective designs for broadband noise absorption. Weighing only 4 lb, this design is a viable candidate for the four-cylinder engine of the Cessna 150 aircraft. The high backpressure of this muffler when mounted on the YO-3A suggests unsuitability for use with six-

cylinder engines. It may be possible to enlarge the ID of the 1" thick baffles (e.g. from 1.75" to 2") to lower the backpressure while maintaining effective noise attenuation.

- Prototype muffler #7: This muffler consisted of an extended (18.5" total length) version of prototype muffler #6, as shown schematically in Figure 14. The sound pressure levels measured for this unit, which weighed 4.3 lb, were very similar to those measured for unit #6, and its measured backpressure was identical. Extending the total muffler length from 15" to 18.5" resulted in minimal improvement in noise attenuation.
- Prototype muffler #8: This muffler consisted of a straight tube sleeve fitted over a cone, as shown schematically in Figure 15. The total length of the device was 13". The tube sleeve measured 4" OD × 11" long and consisted of 100-ppi, 10% dense SiC foam. The cone measured 4" OD × 9" long and was composed of 40-ppi, 10% dense SiC foam. This design weighed 3.8 lb and induced backpressures of 0.8 and 1.1 inHg when mounted on the Cessna 150 and YO-3A aircraft exhausts respectively. Higher sound pressure levels were recorded for this muffler below 400 Hz relative to an unmuffled engine.
- Prototype muffler #9: This muffler duplicated prototype muffler #5, except for a 0.002" perforated metallic sheet enclosing the OD of the SiC foam liner. Despite the sheet, this design induced backpressures of only 0.7 and 1.15 inHg on the Cessna 150 and YO-3A aircraft exhausts respectively. Also, the shimming did not appreciably increase the weight of the unit. This design was shown to generate higher sound pressure levels, particularly at frequencies above 600 Hz, relative to the same design without the sheet.
- Prototype muffler #10: This muffler consisted of three segmented expansion chambers fabricated from 100-ppi, 10% dense SiC foam and two perforated plates having ≈20% flow-through area in the larger expansion chamber. This design, shown schematically in Figure 16, weighed 4.2 lb and induced 0.9 and 1.95 inHg backpressures on the Cessna 150 and YO-3A aircraft exhausts respectively. Of all the prototypes tested, this unit was shown to be the least effective design, yielding no appreciable noise reduction.

Table VI summarizes the average sound pressure levels measured from all prototype mufflers and compares them to the noise attenuation performance of the short and long baseline YO-3A stock pipes. Although the measured sound pressure levels were up to 15 dB_A lower at individual harmonic frequencies above 800 Hz, the overall average noise reduction was only up to 3 dB_A. This is because the overall A-weighted noise levels represent summations of all the harmonics and the broadband noise, and reducing one or two tones cannot reduce the overall perceived noise by more than a factor of two to three. The ground testing results suggest that the SiC foams are generally effective broadband noise absorbers above 800 Hz for general aviation aircraft engines such as the Continental O-200 and O-360.

Sound pressure levels at the engine fundamental frequencies were not significantly affected by the various SiC foam-based prototype mufflers. Varying the foam design configurations did not substantially affect the overall average sound pressure levels. The total muffler weight (including the canning and inlet/outlet pipes) and overall dimensions were shown to be acceptable for retrofitting under existing aircraft cowlings. The backpressures of the mufflers were shown to be tailorable to meet maximum allowable levels while still maintaining effective noise reduction.

The sound pressure level spectra recorded at the data acquisition locations shown in Figure 8 are contained in Appendix B.

4.4.3 Dynamometer Testing

Five of the aforementioned prototype mufflers (#5, 6, 8, 9, and 10, as specified in Section 3.4.3), seven additional units (#11-17, schematics of which are shown in Figures 65-71) machined from RVC foam, one Turbo Tuff commercial muffler, and the baseline straight pipe were all tested on the dynamometer. The average sound pressure levels (measured with the handheld dB meters) and backpressure increases from all the tested prototype mufflers are given in Table IX. The increases in backpressure induced by all units ranged from 0.8 to 1.2 inHg for the Continental O-200 engine, far below the maximum allowable 2 inHg. Much smoother noise spectra were generated from the dynamometer testing compared to those generated from ground testing, indicating that propeller noise was largely eliminated. Thus, the effects of the tested mufflers on engine performance and exhaust noise were much easier to determine. Figures 72A-B show a noise spectrum obtained from dynamometer testing of prototype muffler #8 compared to one obtained from ground testing of the same unit on the YO-3A aircraft.

Sound pressure level spectra for all prototype mufflers tested on the dynamometer are given in Appendix C. Up to 13-dB_A reductions in overall average engine and exhaust noise were measured for units #9 and #17 relative to the baseline straight pipe. Although all prototype mufflers had little effect on sound pressure level at the engine fundamental frequencies (below 800 Hz), significant noise attenuation was observed above 800 Hz, which again agrees well with the data obtained from bench and ground testing.

Dynamometer testing eliminates all propeller noise and directly measures the noise reduction capability of the exhaust system. Such testing is thus the only effective method of measuring the true sound absorption/noise attenutation performance of candidate muffler systems.

4.5 Catalytic Converter Evaluation

Tables X and XI show the emissions produced by the Continental O-200 engine without and with SiC foam catalytic converters respectively. Figure 73 shows the conversion efficiency of the converters calculated from these data. The catalytic converter/acoustic liner reduced emissions by an average of ≈65%. The emissions composition and conversion efficiency varied as a function of engine speed. Engine-out emissions ranged from 3.4 to 12.0% CO, 63 to 110 parts per million (ppm) NO_x, and 250 to 1250 ppm HC over a range of engine speeds from 1000 to 2500 rpm. The converter/acoustic liner reduced emissions from 40 to 90%, depending on the type of emission and engine speed. The SiC foam substrate performed well and was demonstrated to be technically feasible, with the catalyst adhering well to the foam and no visible wear imparted to either catalyst or foam. All tested SiC foam specimens showed high durability and survivability.

A 40-90% reduction in aircraft emissions is estimated to reduce the CO, HC, and NO_x emissions by 60%, 70%, and 80% respectively. This would result in the elimination of 23,000 tons of CO, 200 tons of HC, and 31 tons of NO_x emissions emitted annually by general aviation aircraft in California alone, if such aircraft were equipped with SiC foam-based mufflers.

An estimate of emissions from piston-powered general aviation aircraft for both the U.S. and California was extrapolated from the emissions data gathered in this project and the reported hours flown by piston-powered GA aircraft in the U.S. in 1996 [4]. The emissions forming the baseline for this estimate, measured using the automotive five-gas analyzer, represent a first-order approximation only; a detailed study should be commissioned to measure a more precise estimate.

The methodology of this estimate involved the volume percent emissions from a Continental O-200 engine measured using the five-gas analyzer and the calculated volume pumping capacity of this engine for the measured rpm. These calculations yielded the volume of emissions per hour produced by the engine at a given load. The engine-out emissions were reported in grams per hour (g/hr) at a given engine speed. Weighted average emissions were then calculated given the normal in-flight operating characteristics of an aircraft equipped with an O-200 engine. The operational weighting for this engine was chosen as 95% of running hours conducted at cruising speed (2500 rpm, ≈100 hp) and 5% of running hours conducted at on-ground idle (1500 rpm, no load). It was assumed for this estimate that a total of 22.2 million hours were flown in the U.S. in 1996 by single-engine, piston-powered GA aircraft. All multi-engined, piston-powered aircraft were assumed to have twin O-200 engines (although the O-360 engine is the workhorse engine of the U.S. general aviation fleet, emissions data were measured using the O-200 because of availability and safety considerations).

The estimate of weighted emissions during operation of the O-200 engine assumed that the engine emitted 15,728 g/hr CO, 116 g/hr HC, and 15.6 g/hr NO_x. From this data, an estimate of annual emissions from piston-powered general aviation aircraft was extrapolated. The estimate for California emissions was 38,429 tons per year (tpy) CO, 283 tpy HC, and 38 tpy NO_x. The addition of catalyst-coated acoustic liners to these aircraft is estimated to reduce these amounts to 15,223 tpy CO, 83 tpy HC, and 7 tpy NO_x, or a 60% reduction in CO, a 70% reduction in HC, and an 80% reduction in NO_x due to the enabling catalyst-coated CVD SiC foam technology.

4.6 Flight Testing

Table XII summarizes the results of engine backpressure measurements conducted before flight testing. At all engine speeds, the SiC foam-based exhaust system exhibited low backpressure, and the backpressure at all engine speeds was lower than that produced by the Cessna 150 OEM exhaust system. Lower backpressure was expected to result in improved aircraft performance, which was confirmed during flight testing.

Tables XIII and XIV summarize the takeoff (flight profile #1) and low-approach (flight profile #2) noise levels, respectively, measured during flight testing of the Cessna 150 aircraft equipped with SiC foam-based mufflers. When equipped with SiC foam mufflers, the aircraft emitted an average takeoff sound level of 69.3 dB_A, a reduction of 0.8 dB_A from the OEM system. The lower backpressure of the SiC foam-based exhaust system also resulted in an increase in climb rate of 100 ft/min, and the pilot reported improved flight performance and faster aircraft response. The 0.8-dB_A reduction in sound level is much lower than the 13 dB_A reduction measured using the dynamometer. Furthermore, the sound measured from the aircraft equipped with SiC foam mufflers during low-approach testing was 0.3 dB_A greater than when using the OEM system. Since the dynamometer was designed to eliminate propeller noise from the system, it may be concluded that propeller noise dominates the engine/propeller flight test system.

Post-flight examination revealed that the SiC foam inserts shifted in their steel muffler cans during flight, causing "machining" of the foam by the cans. The movement of the SiC foam inserts within the steel cans caused substantial wear on the foam, which was not observed during on-engine ground testing. Dynamometer testing had indicated that a compliant layer between the steel can and the SiC foam was not required. However, the flight testing indicated that a compliant layer would in fact be required between the SiC foam broadband sound absorber and the steel can. Compliant layers were developed for automobile catalytic converters because the ceramic substrates in such converters wore against their steel cans during normal operation. Since the advent of the compliant interlayers, 300 million automobile catalytic converters have been fielded, which generally last for the lifetime of the vehicle. The SiC foam was not eroded by the exhaust gas or sound energy from the engine exhaust pulse, and the material exhibited excellent resistance to the high exhaust gas temperature, corrosion, and sound vibration.

5. CONCLUSIONS AND RECOMMENDATIONS

In this project, more than 30 prototype muffler configurations were developed and evaluated, along with seven commercial mufflers, for their acoustic characteristics in use on general aviation aircraft. Numerous test methods were developed to cost-effectively screen the various newly developed muffler designs. Methods for acoustic evaluation included insertion loss bench testing, dynamometer testing, and ground testing. The most promising muffler configuration was then downselected for flight testing. Based on the test results, the following conclusions can be drawn:

- Dynamometer data confirmed that SiC foam-based exhaust systems can reduce engine noise by up to 13 dB_A.
- Testing of the various commercial mufflers indicated that no significant noise reduction was obtained using any of the off-the-shelf muffler designs.
- Data from SYSNOISE modeling, insertion loss bench testing, ground testing, and dynamometer testing all showed that no muffler configuration was capable of significantly reducing sound pressure levels at the fundamental engine frequencies.
- Open-cell SiC foams were shown to be generally effective as broadband noise absorbers at frequencies above 800 Hz, particularly for larger general aviation engines (e.g. the Continental O-360).
- The total weight, including canning and inlet/outlet pipes, and overall dimensions of the prototype mufflers were shown to be feasible for retrofitting under the engine cowlings of general aviation aircraft.
- The backpressures induced by the majority of the prototype mufflers were well below the maximum allowable level of 2 inHg.
- Although noise levels at the fundamental engine frequencies were essentially unaffected, significant noise attenuation was observed above 800 Hz; prototype mufflers #9 and #17 reduced the overall engine noise of the Cessna 150 aircraft by up to 13 dB_A.
- Tuning the SiC foam configurations to reduce noise at the engine fundamental frequencies is not a straightforward task, possibly requiring a combination of passive ceramic foam with an active system.
- A catalyst-coated SiC foam acoustic liner exhaust system can reduce piston-powered aircraft engine emissions by 40-90%. Further optimization is required to enhance this performance, and catalyst durability must be confirmed.
- During flight testing using the Cessna 150 aircraft, the SiC foam-based exhaust system yielded a 0.8-dB_A decrease in noise levels during takeoff. However, it also yielded a 0.3-dB_A increase in low-approach (flyover) noise levels. Flyover noise from the Cessna 150 may be controlled by attenuating propeller noise levels.
- The lower backpressure of the SiC foam-based exhaust system resulted in an increase in climb rate of 100 ft/min for the Cessna 150 aircraft.
- The SiC foam-based exhaust system will require a compliant layer between the foam broadband sound absorber and its steel casing to eliminate shifting-induced wear.
- The SiC foam-based exhaust system can be mounted entirely within the existing cowling of a Cessna 150 aircraft.
- Flight testing confirmed that SiC foam-based broadband sound absorbers can withstand the high temperatures, corrosion, gas velocities, and sound pulses of the general aviation aircraft exhaust environment.

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3. A.J. Sherman and S. Heng, "Noise Reduction System for General Aviation Aircraft," Final Report (ULT/TR-94-6664), Contract NAS3-27230, Ultramet for NASA Lewis Research Center, Cleveland, OH, 1994.

4. Aircraft Owners and Pilots Association (AOPA, Frederick, MD), World Wide Web page, http://www.aopa.org.

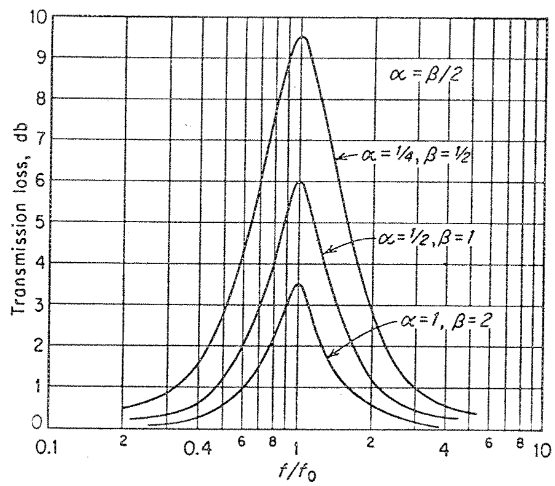


Figure 1.
Frequency dependency of a typical reactive muffler design

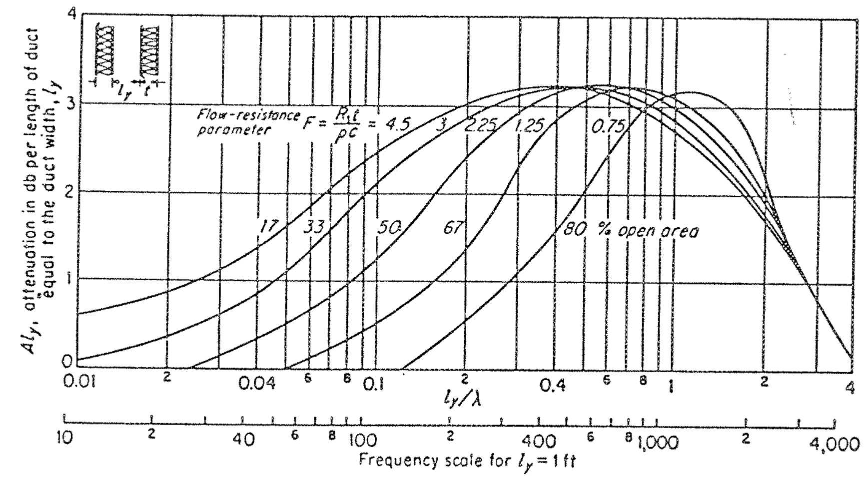


Figure 2.
Frequency dependency of a typical dissipative muffler design

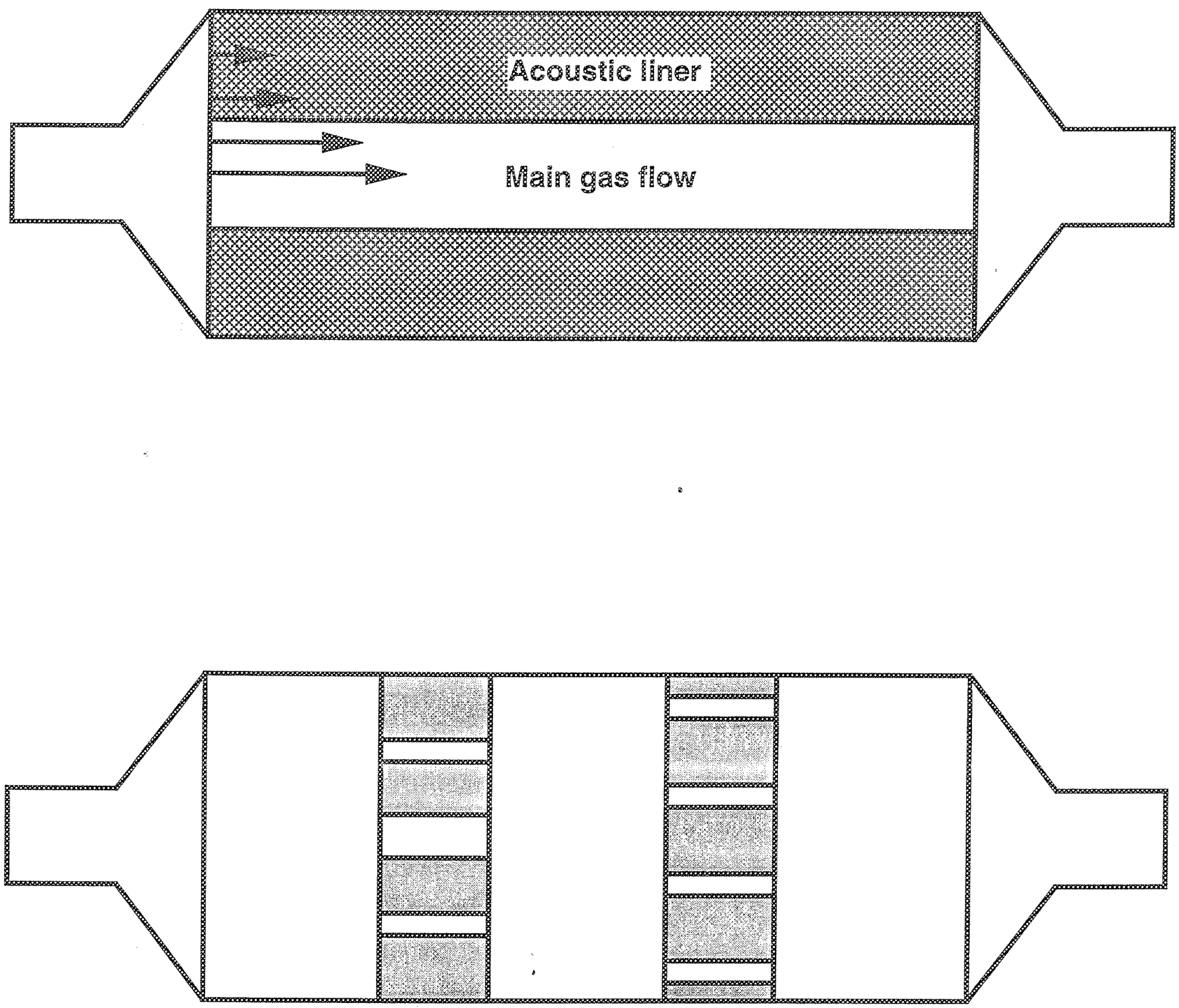
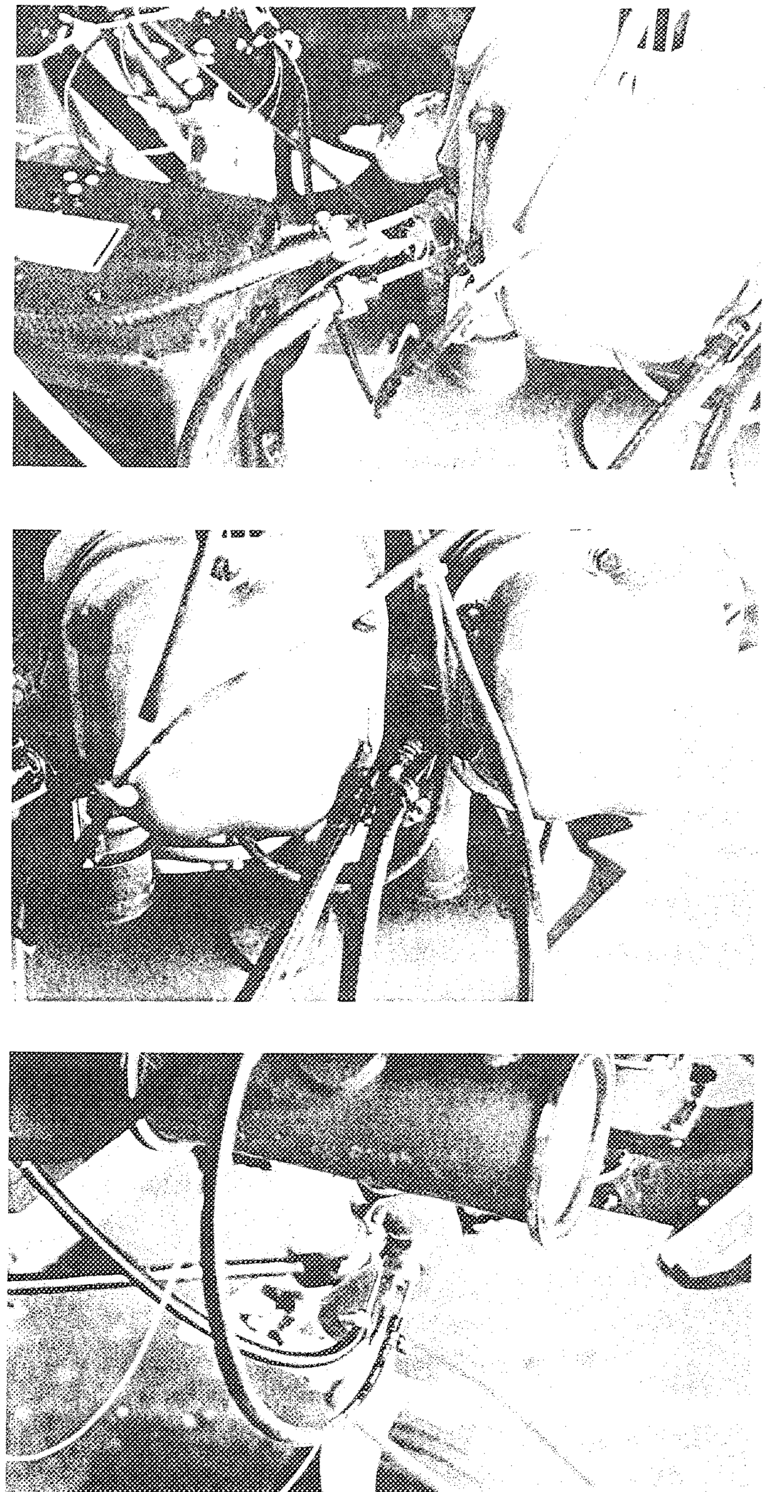
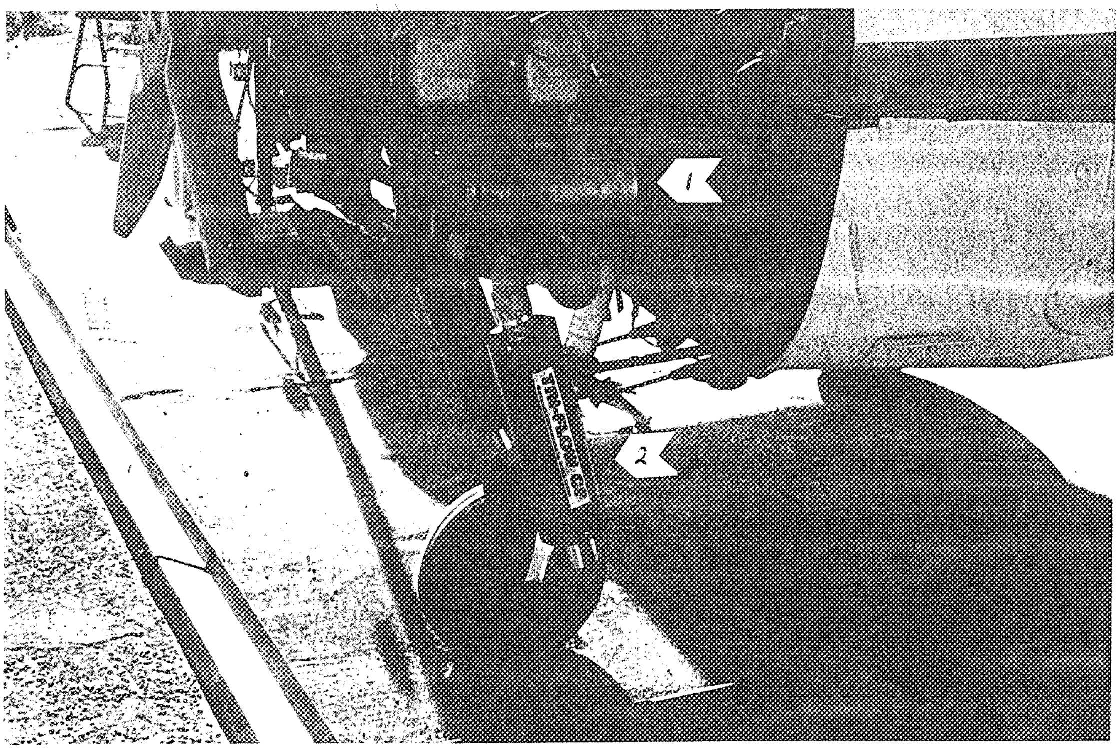


Figure 3.
Schematic of lined expansion chamber muffler design (top) and expansion chamber muffler with flow-through baffles (bottom)



Figures 4A-C.
Liquid-cooled pressure transducers used for measurement of Cessna 150 engine noise: on cylinder #3 (top), on cylinder #1 (middle), and on tailpipe (bottom)



[1]stock muffler
[2]commercial muffler (Tri Flow Ceramics pictured)

Figure 5.
Commercial muffler test setup on Cessna 150 aircraft

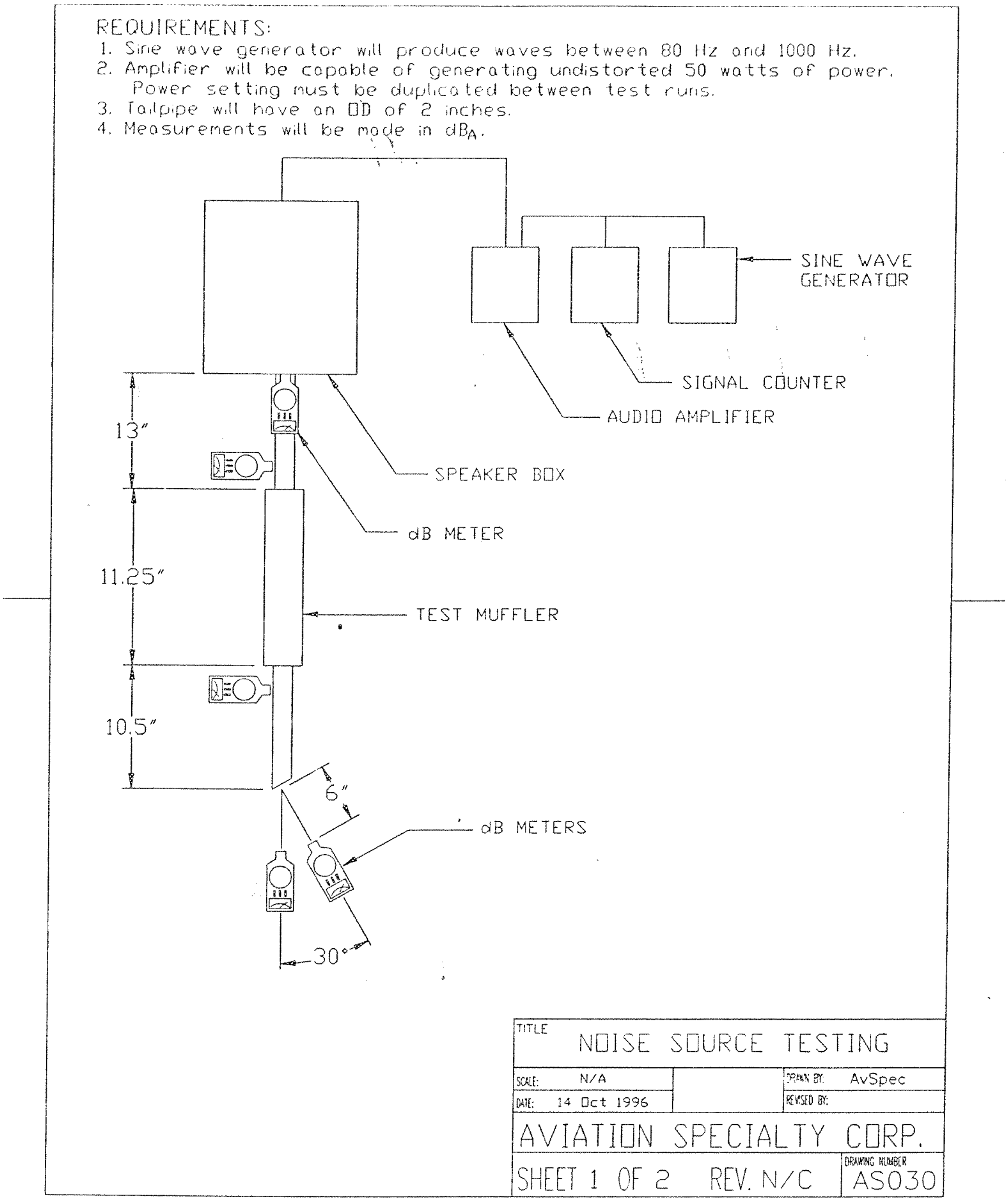
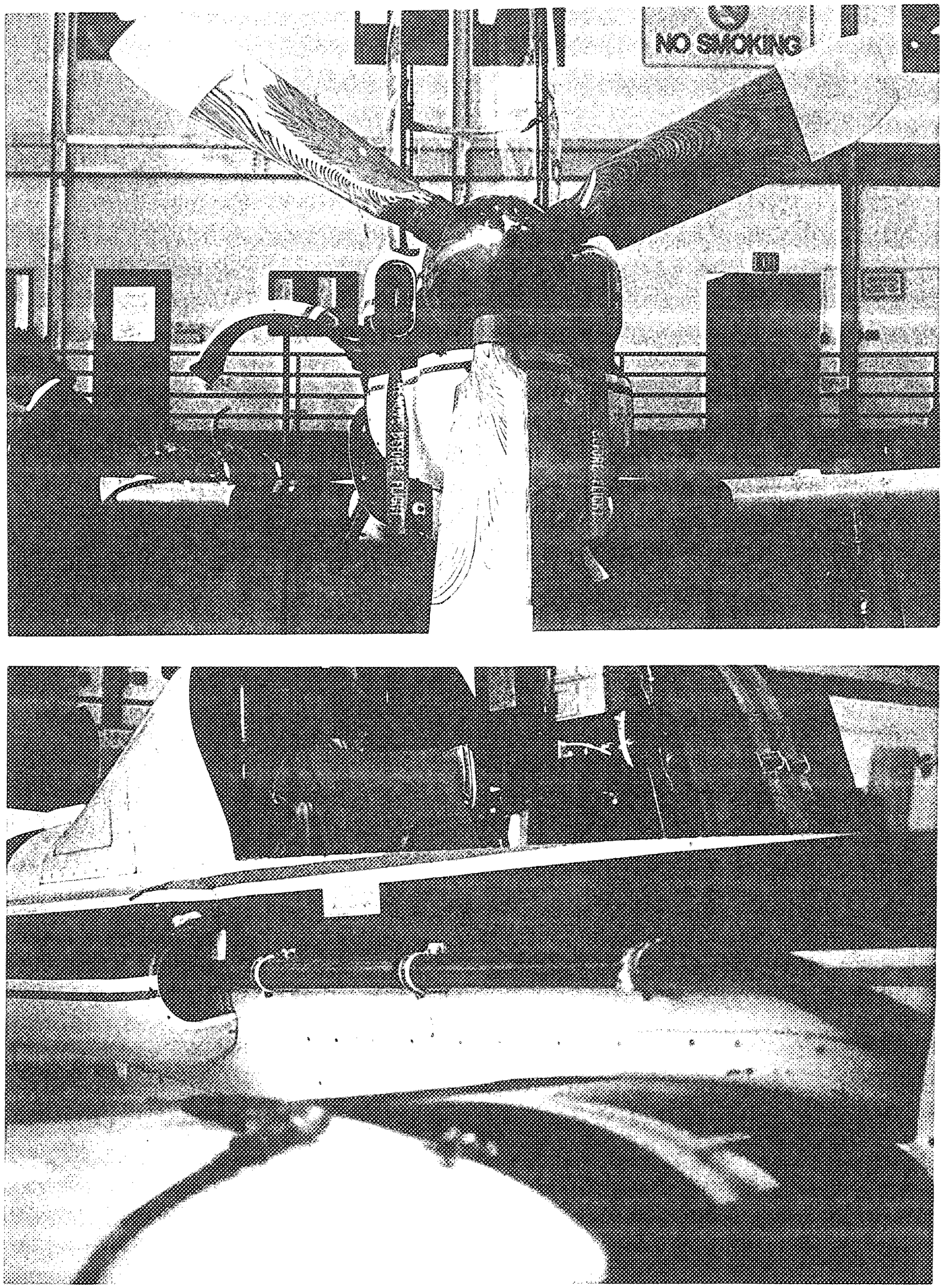
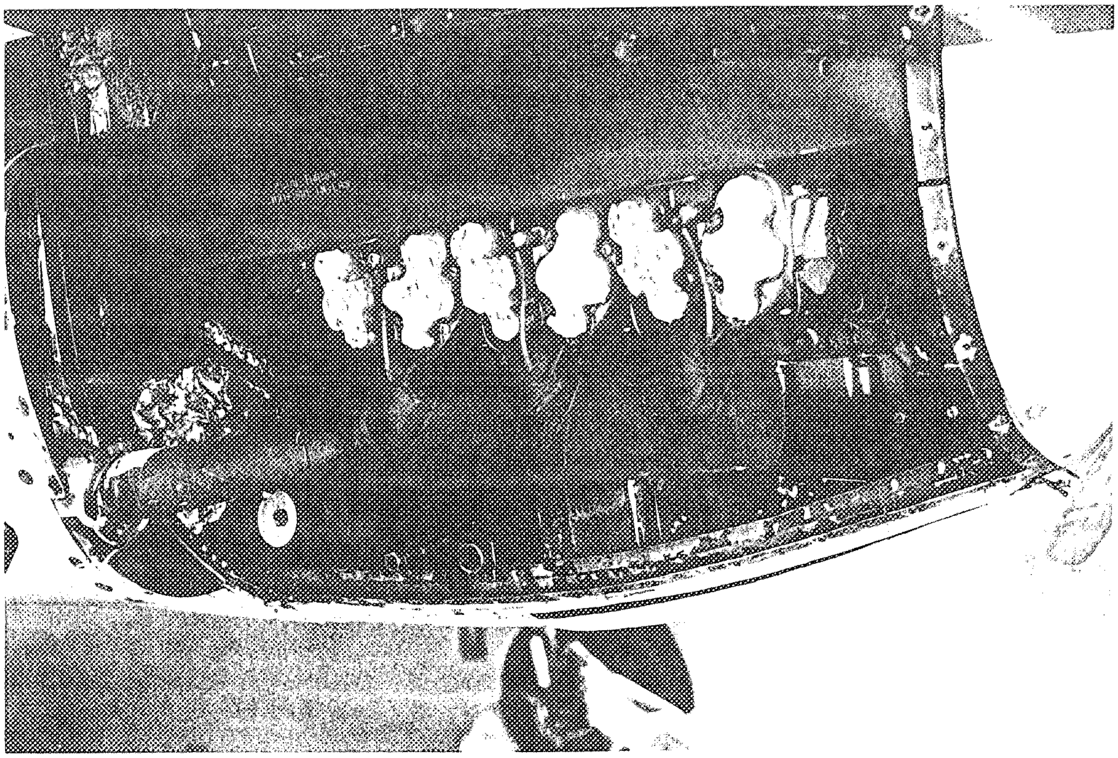
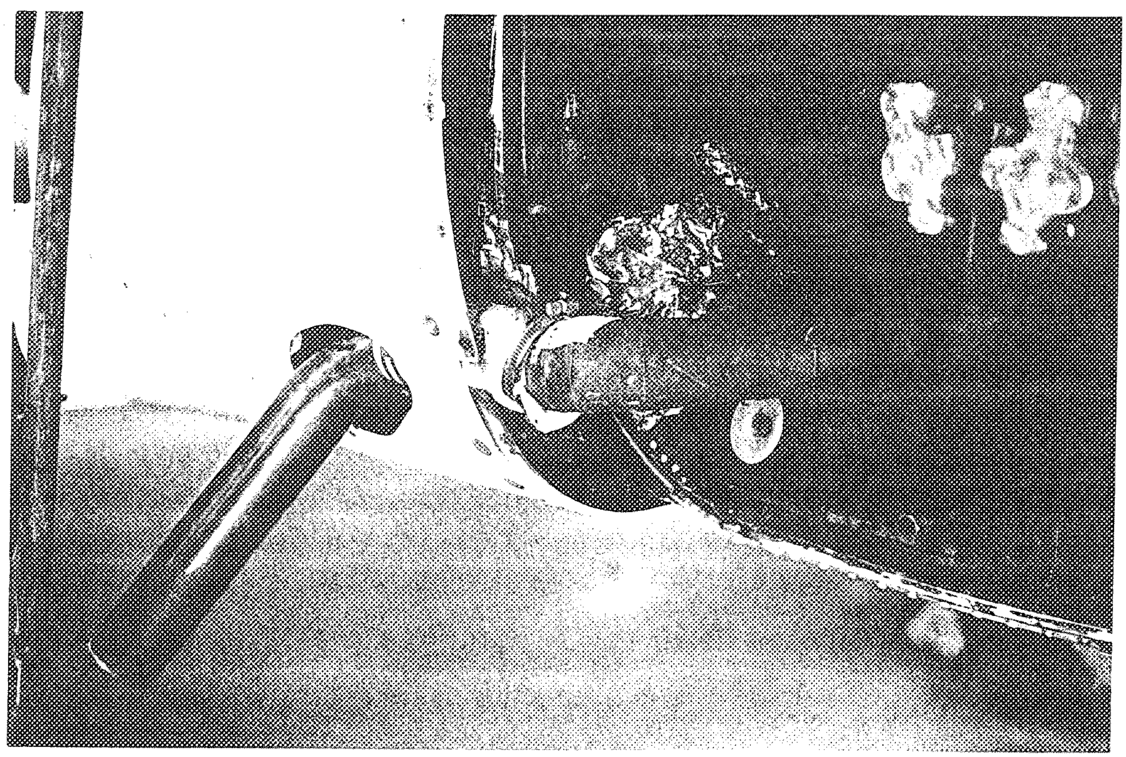


Figure 6.
Schematic of noise source test apparatus used for initial screening of prototype mufflers



Figures 7A-B.
NASA YO-3A research aircraft, showing noise-reducing design features
(top: low-noise propeller; bottom: stock long-pipe muffler)





Figures 7C-D.
NASA YO-3A research aircraft, showing engine (top) and stock short-pipe exhaust connection (bottom) used for testing of prototype mufflers

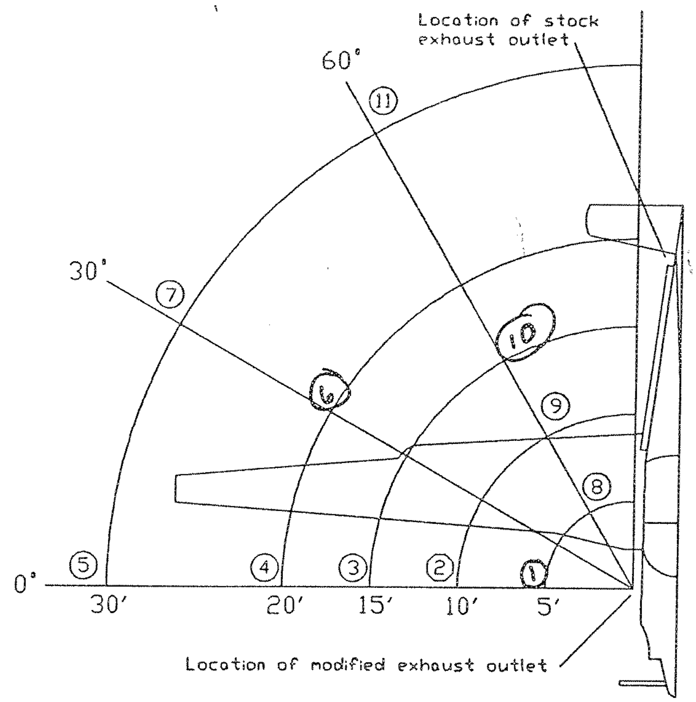


Figure 8.
Schematic of noise mapping arcs originating from exhaust of YO-3A aircraft, showing locations at which noise measurements were taken

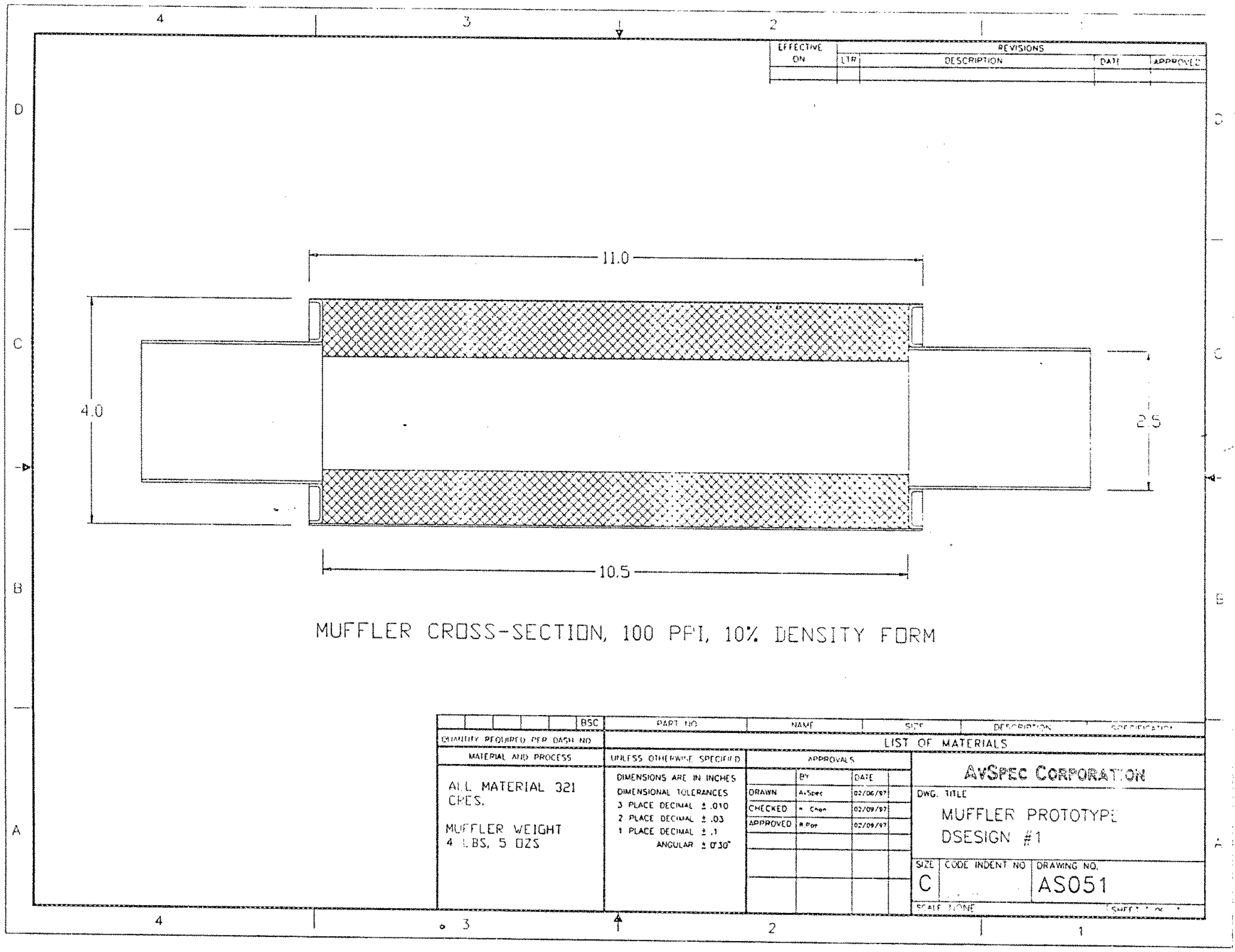


Figure 9.
Schematic of prototype muffler design #1: a 4" OD × 11" long straight pipe containing a 4" OD × 2" ID × 10.5" long liner of 100-ppi, 10% dense SiC foam

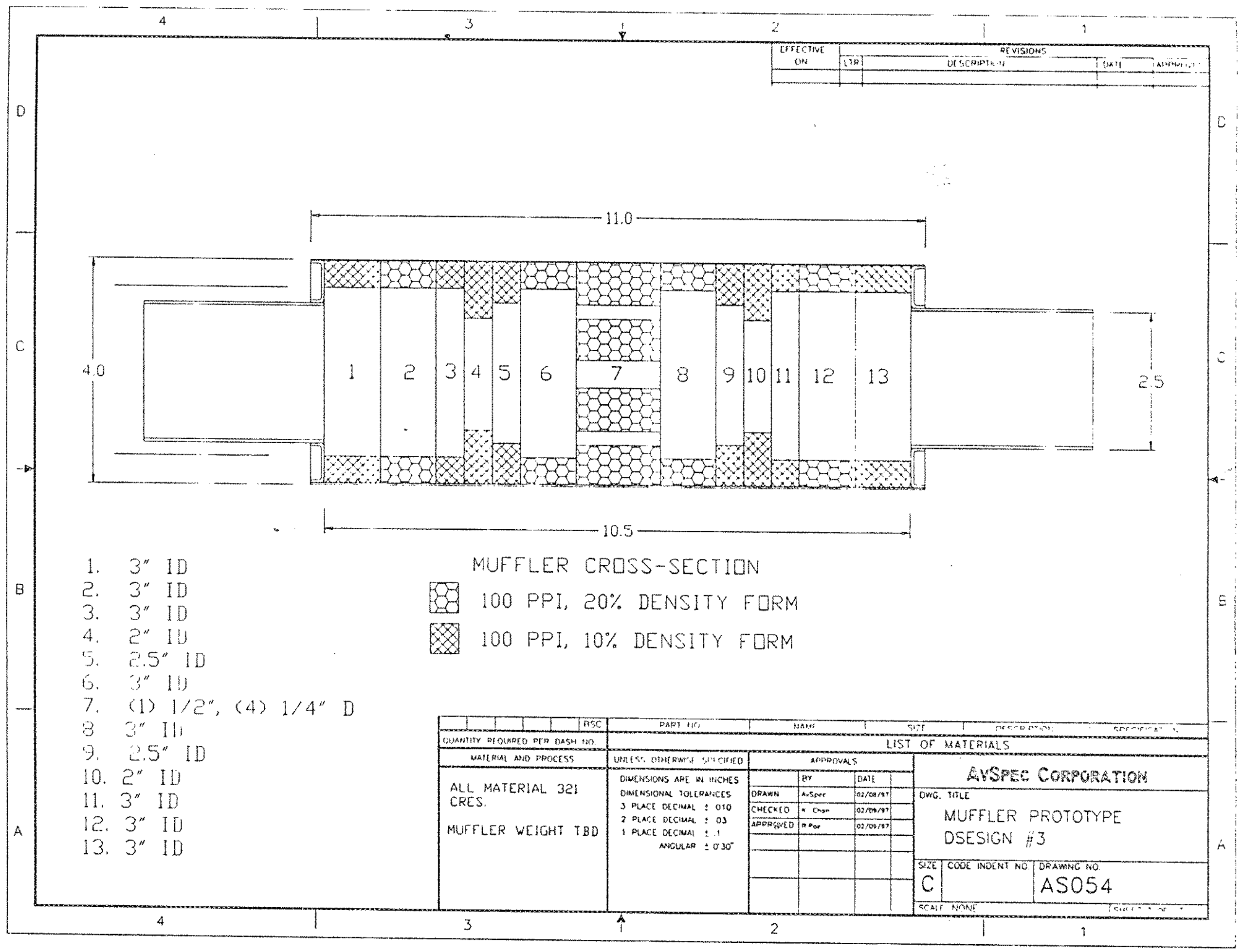


Figure 10.
Schematic of prototype muffler design #3: a 4" OD × 11" long straight pipe containing perforated 100-ppi, 10 and 20% dense SiC foam plates and baffles of various thicknesses and inner diameters

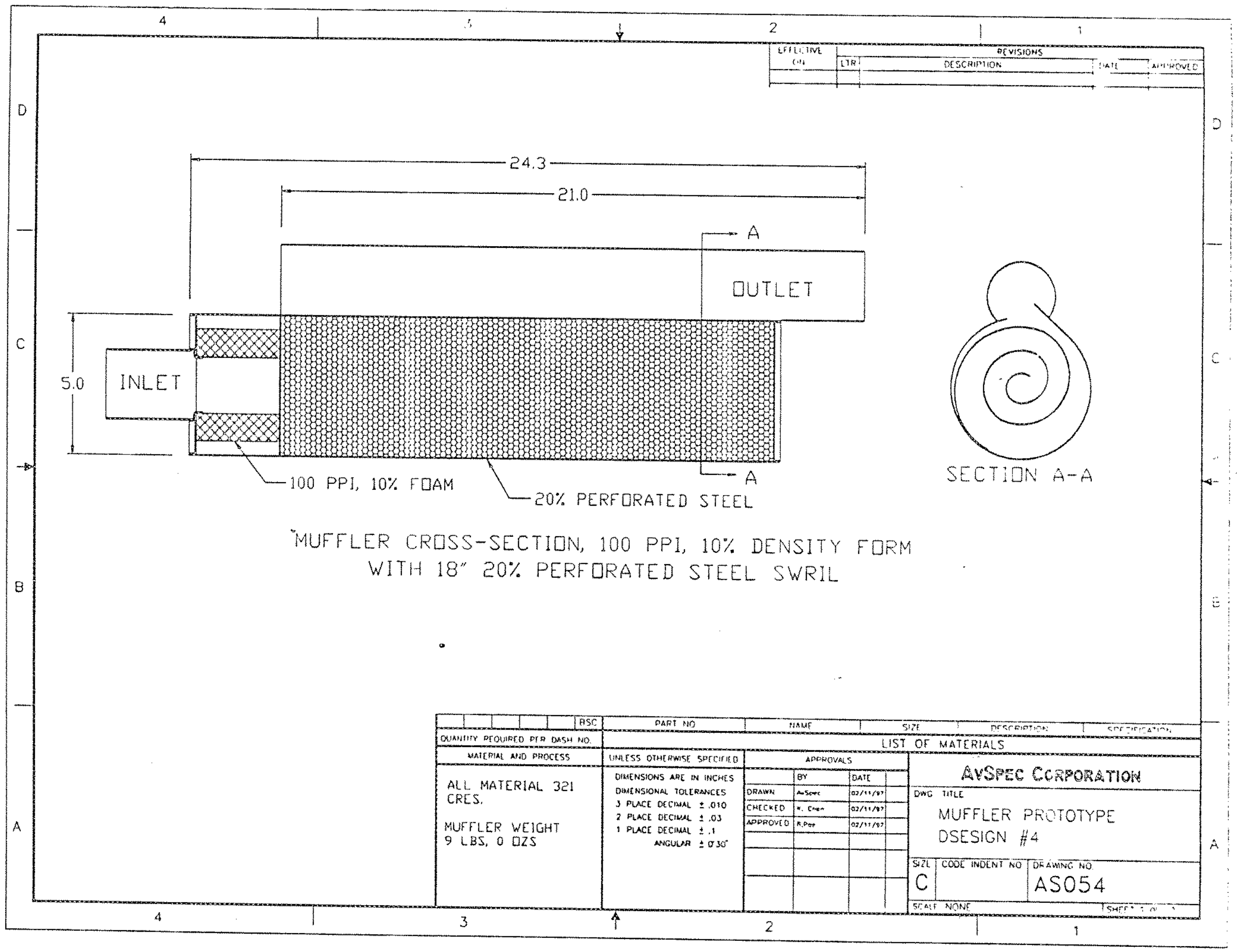
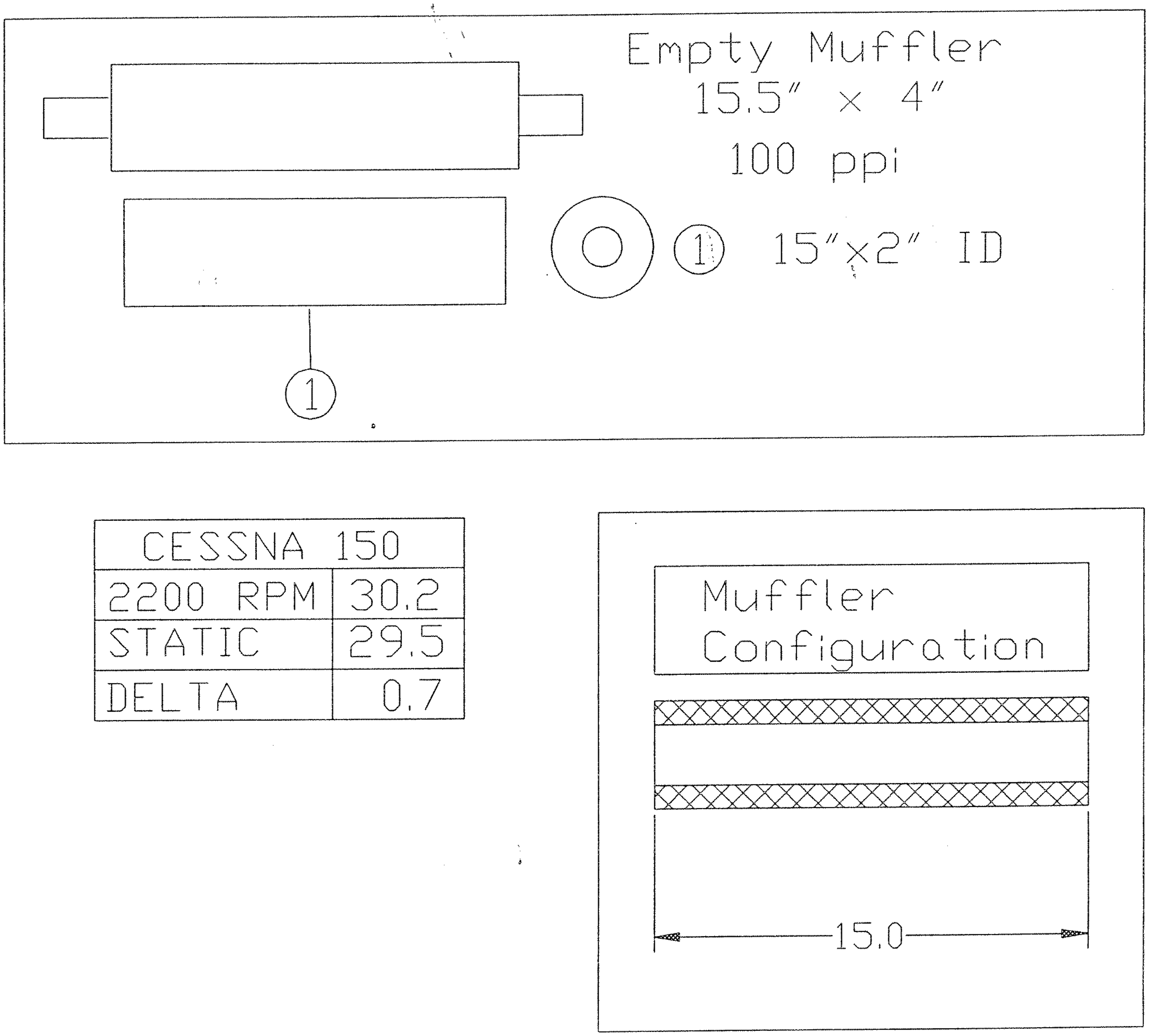
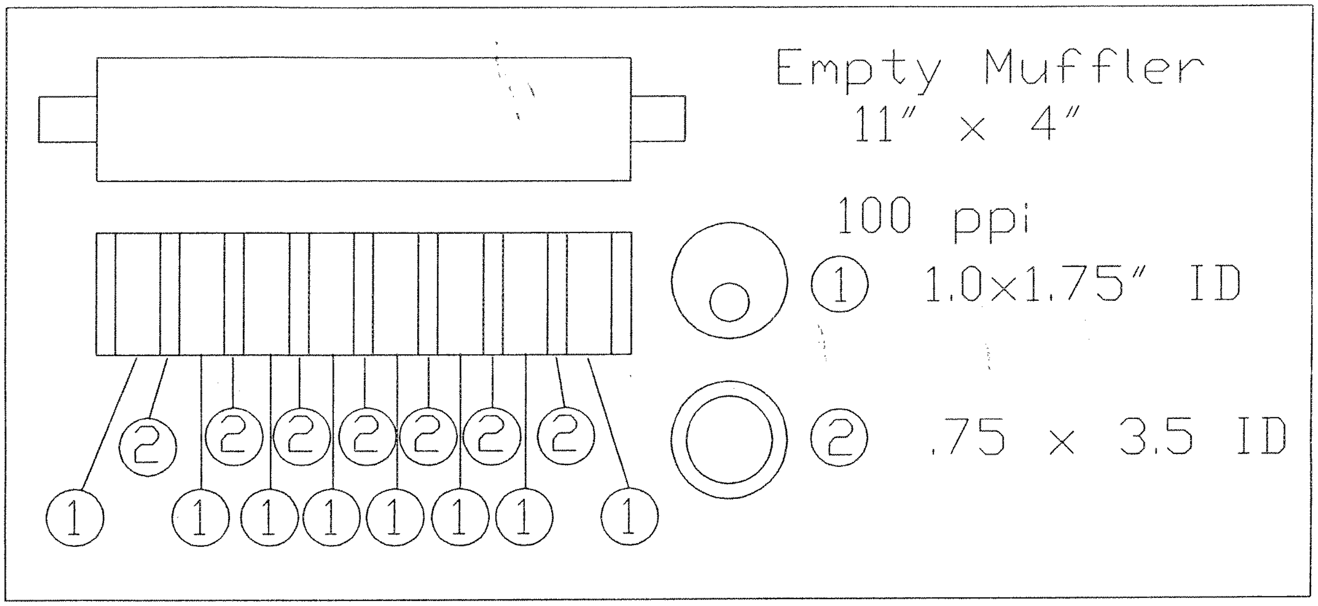


Figure 11.
Schematic of prototype muffler design #4: a 5" OD straight pipe with a 21" long offset outlet containing a 100-ppi, 10% dense SiC foam liner at inlet and a swirled, 20% perforated internal steel sheet



CESSNA 150	
2200 RPM	30.2
STATIC	29.5
DELTA	0.7

Figure 12.
Schematic of prototype muffler design #5: a 4" OD × 15.5" long straight pipe containing a 4" OD × 2" ID × 10.5" long liner of 100-ppi, 10% dense SiC foam



CESSNA 150	
2200 RPM	30.6
STATIC	29.5
DELTA	1.1

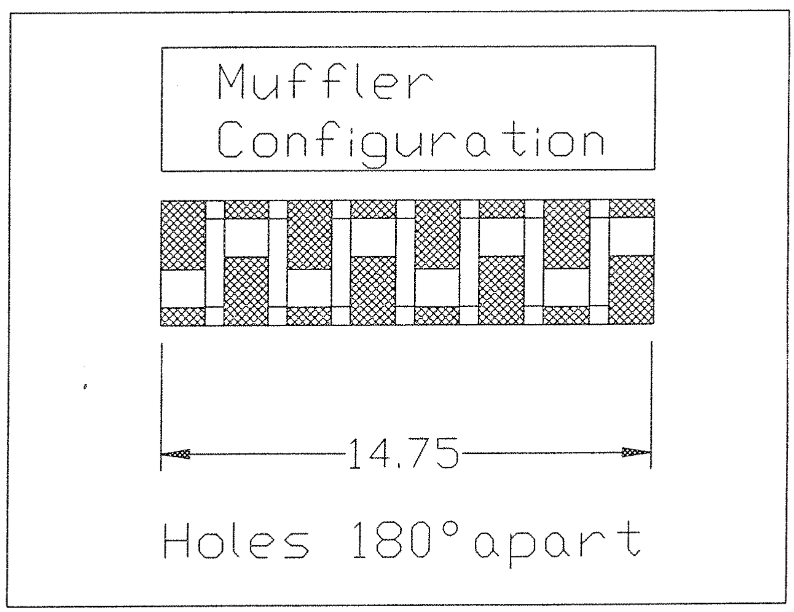
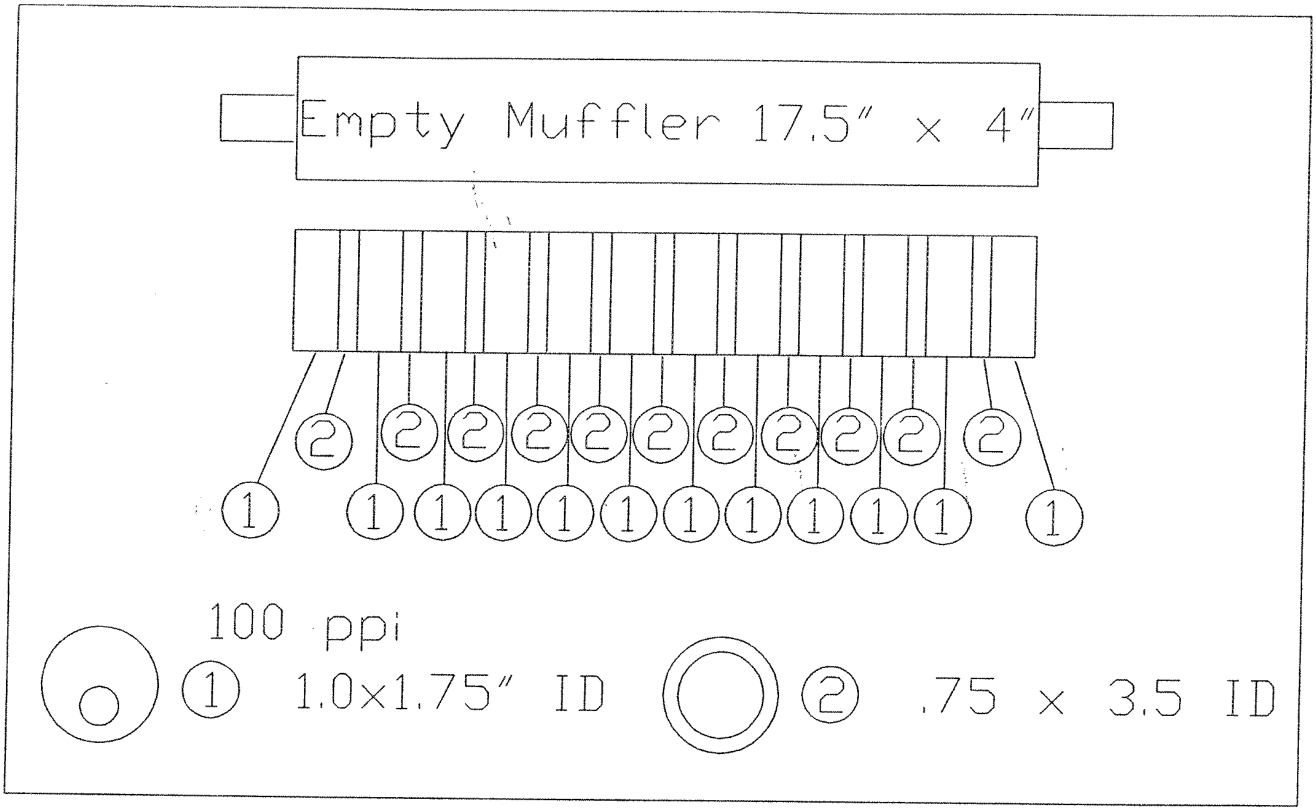


Figure 13.
Schematic of prototype muffler design #6: a 4" OD × 11" long straight pipe containing 4" OD × 1.75" ID × 1" thick, 100-ppi, 10% dense SiC foam baffles with offset core holes alternating with thin 10-ppi, 10% SiC foam spacer rings



CESSNA 150	
2200 RPM	30.8
STATIC	29.5
DELTA	1.3

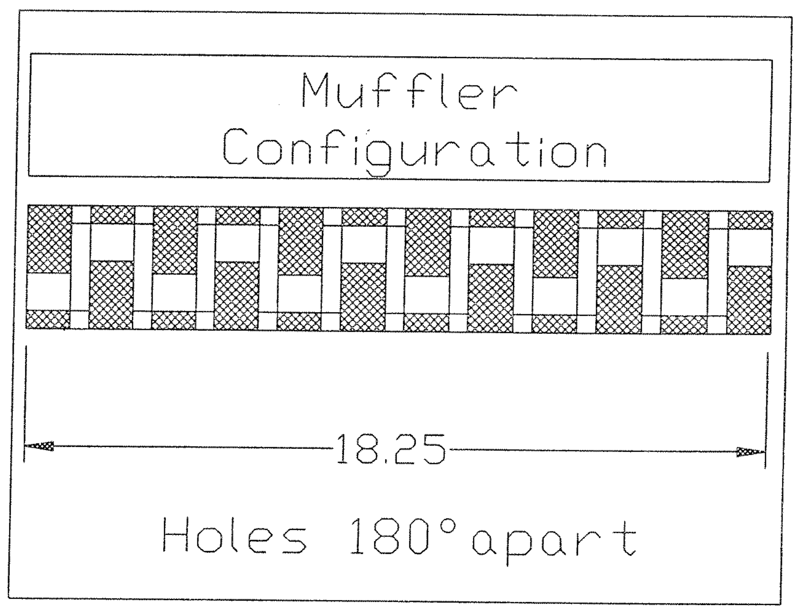


Figure 14.
Schematic of prototype muffler design #7: a 4" OD × 17.5" long straight pipe containing 4" OD × 1.75" ID × 1" thick, 100-ppi, 10% dense SiC foam baffles with offset core holes alternating with thin 10-ppi, 10% SiC foam spacer rings

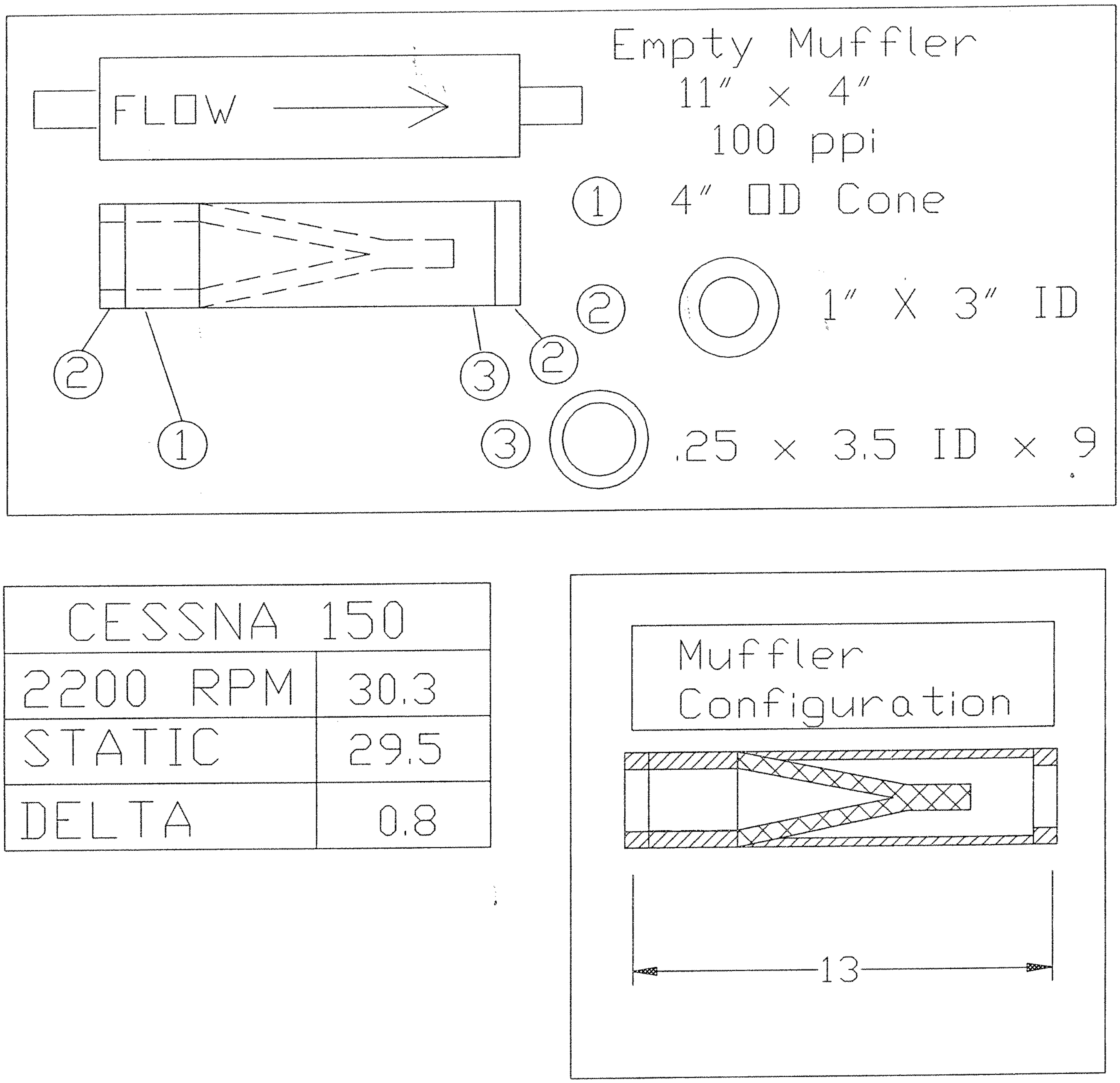
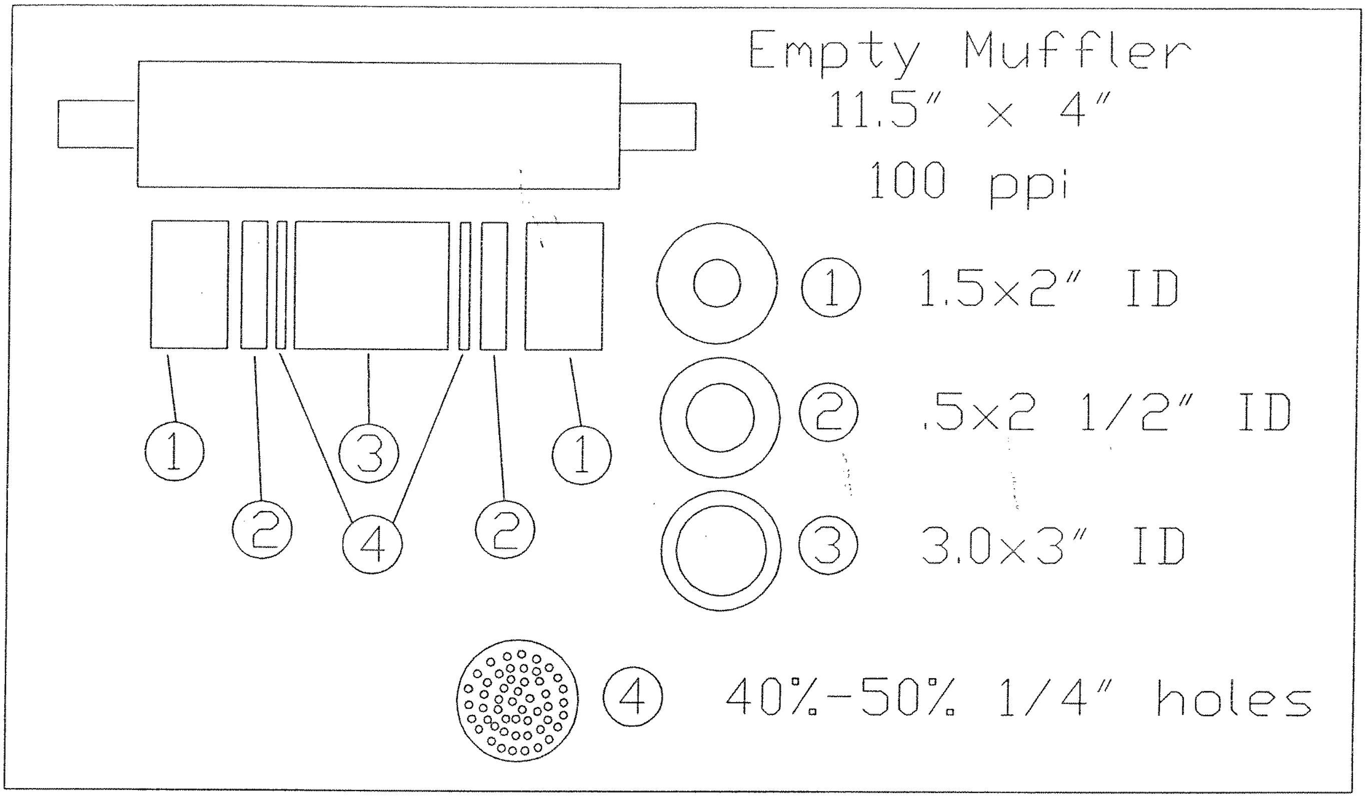


Figure 15.
Schematic of prototype muffler design #8: a 4" OD × 11" long straight pipe containing a 4" OD, 40-ppi, 10% dense SiC foam cone fitted partially inside a 4" OD × 3.5" ID × 9" long, 100-ppi, 10% dense SiC foam cylinder



CESSNA 150	
2200 RPM	30.4
STATIC	29.5
DELTA	0.9

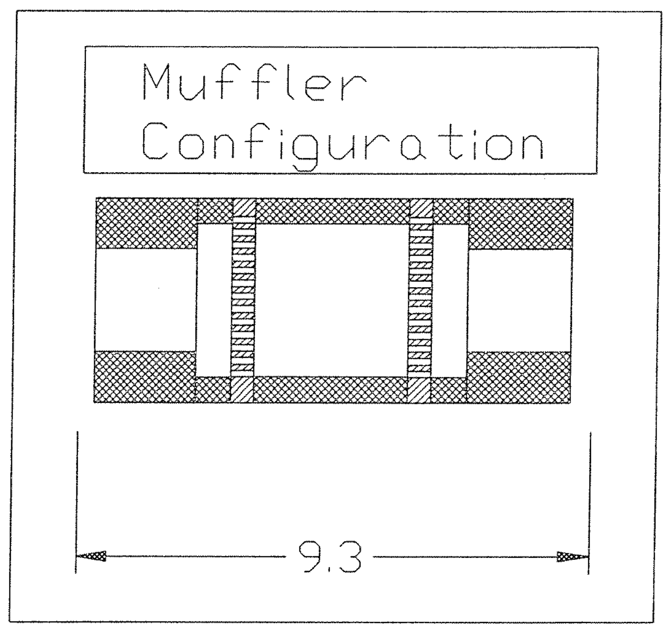
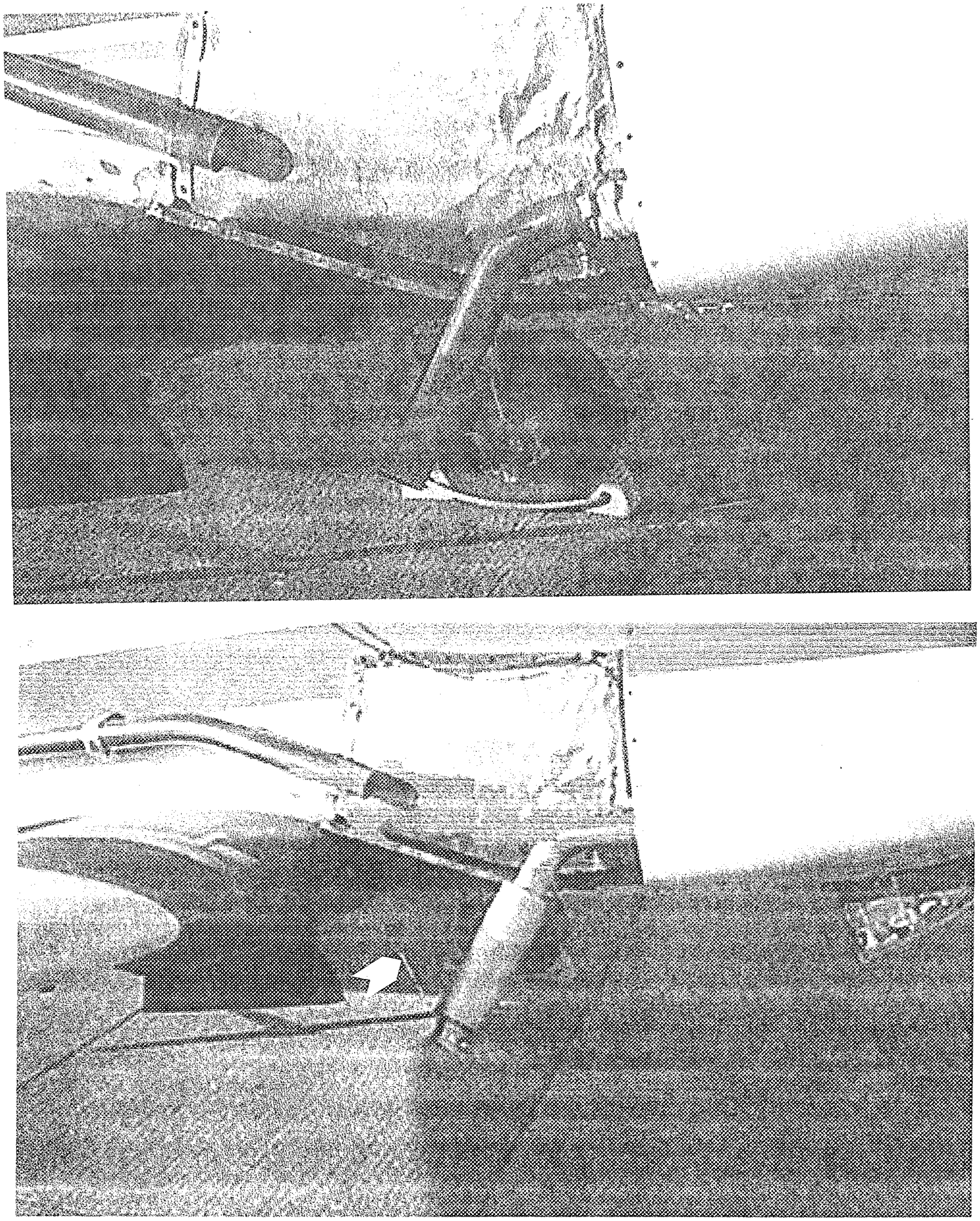


Figure 16.
Schematic of prototype muffler design #10: a 4" OD × 11.5" long straight pipe containing three segmented expansion chambers of 100-ppi, 10% dense SiC foam of varying inner diameters and thicknesses and two 40-50% perforated plates



Figures 17A-B.
Stock short-pipe extension used for baseline testing on YO-3A aircraft (top) and installed prototype muffler (bottom); arrow shows steel mounting flange to prevent muffler vibration

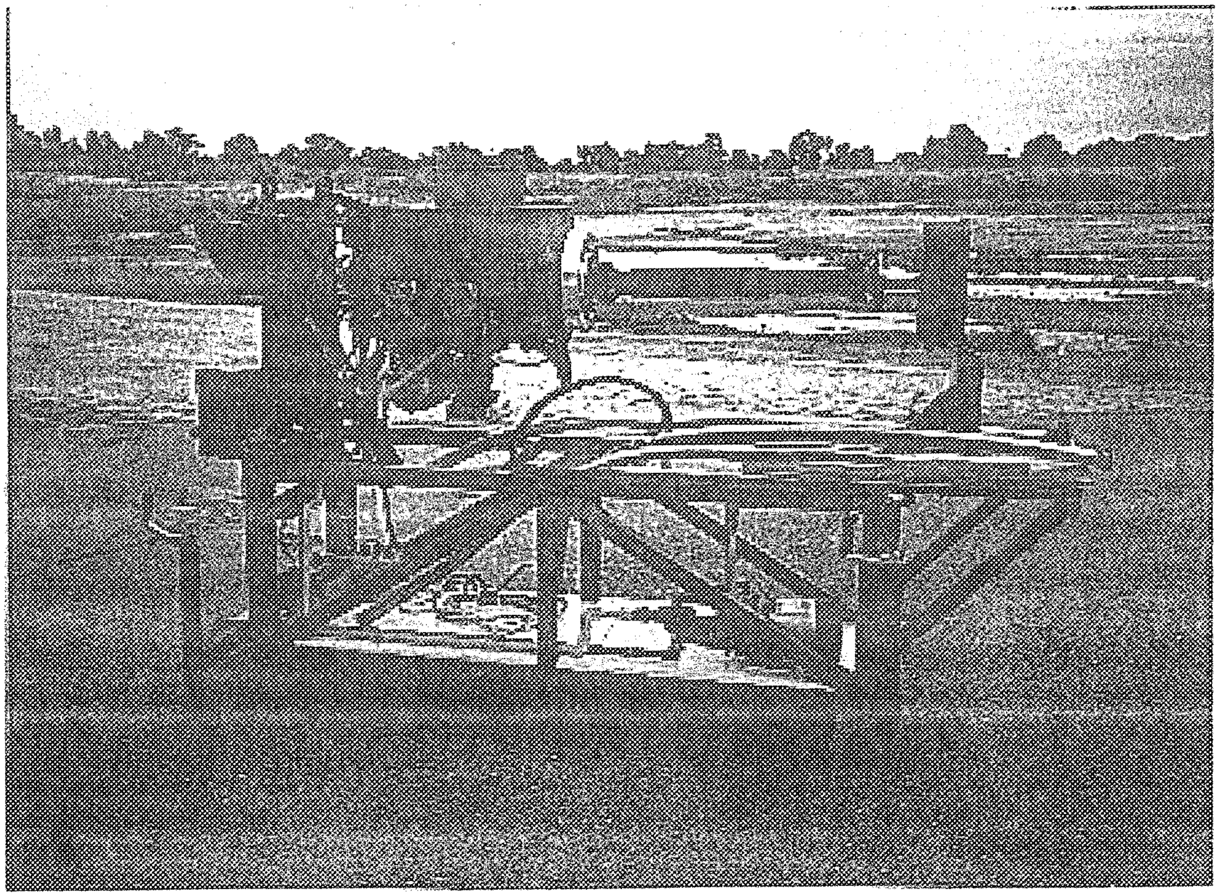


Figure 18.
Final dynamometer assembly,
without engine cooling system and acoustic chamber

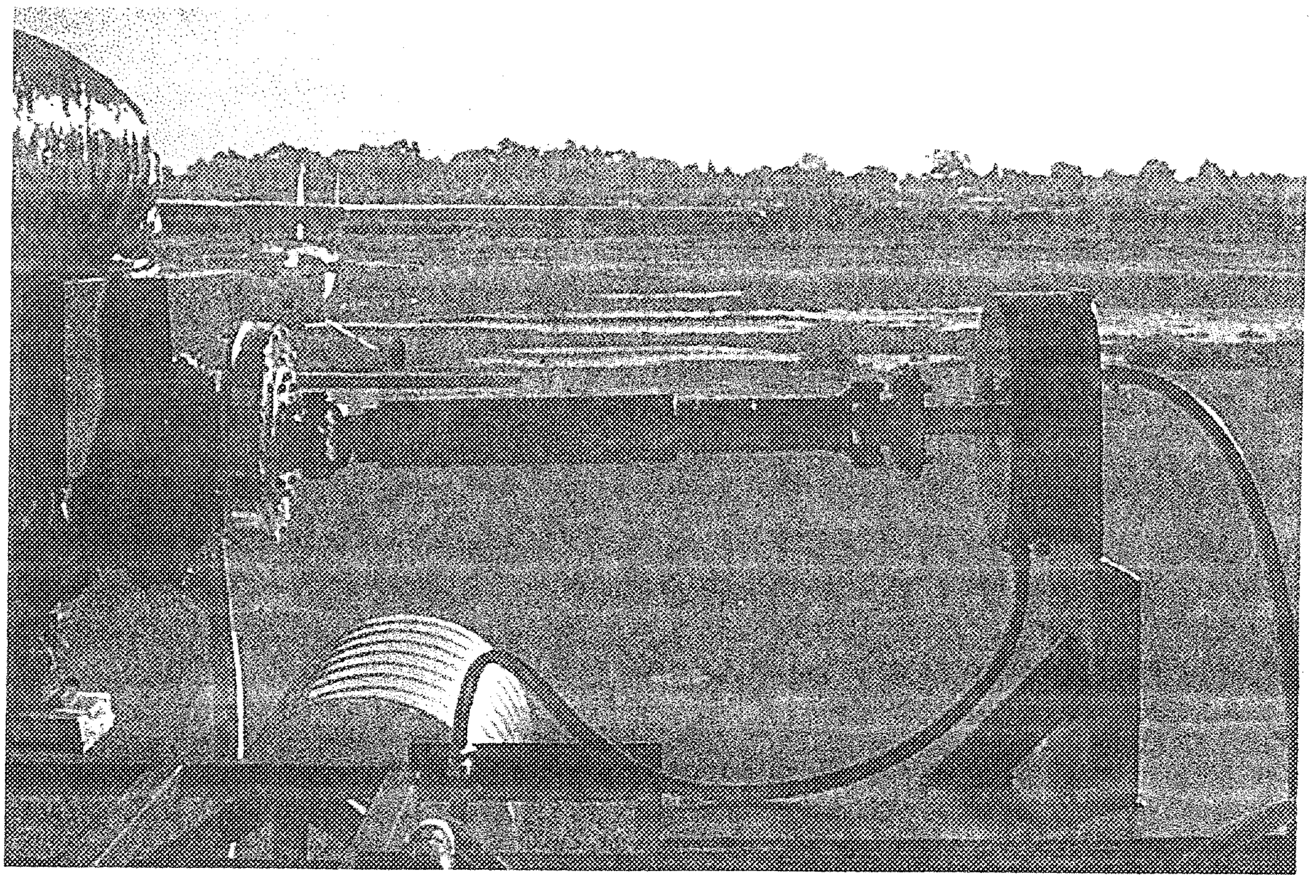


Figure 19.
Water brake of final dynamometer assembly,
with drive shaft connection to engine

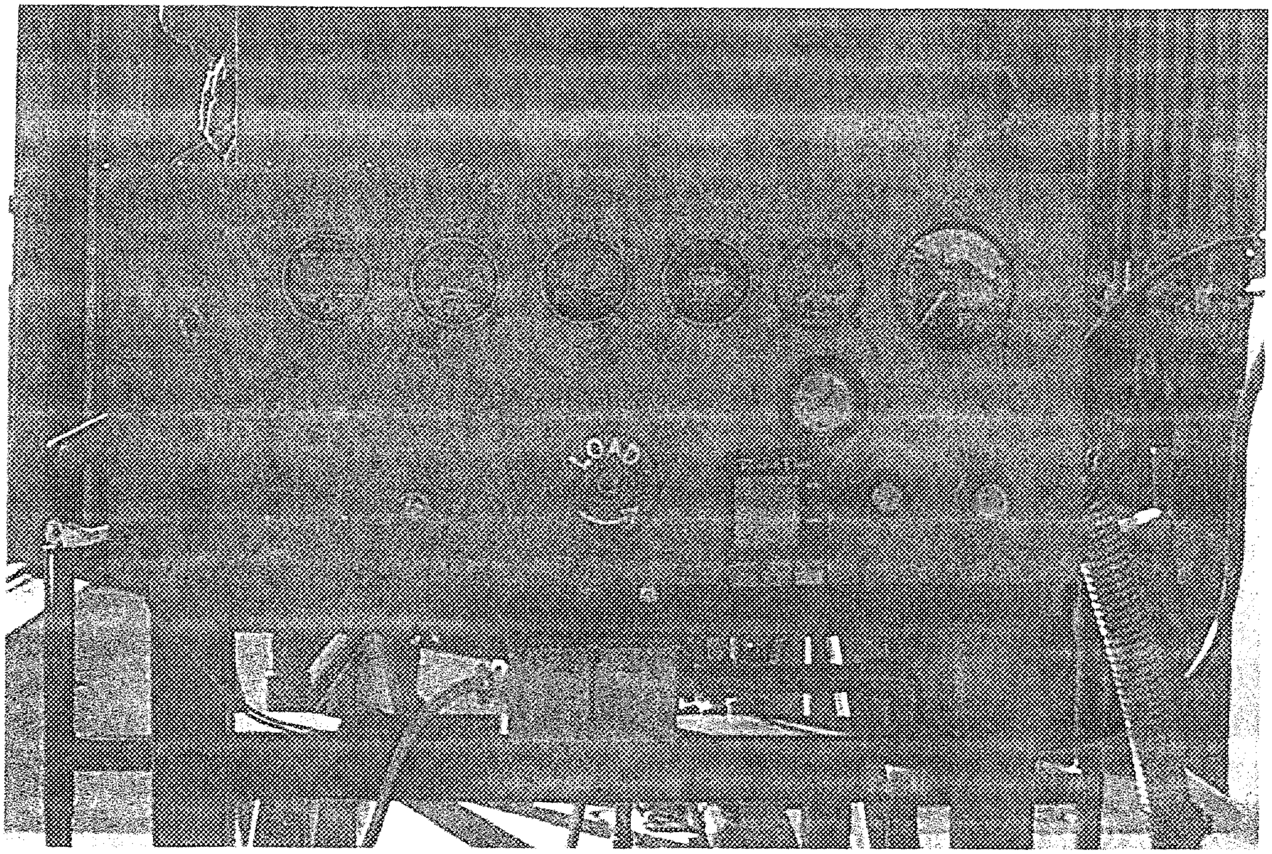


Figure 20.
Instrumentation panel of final dynamometer assembly

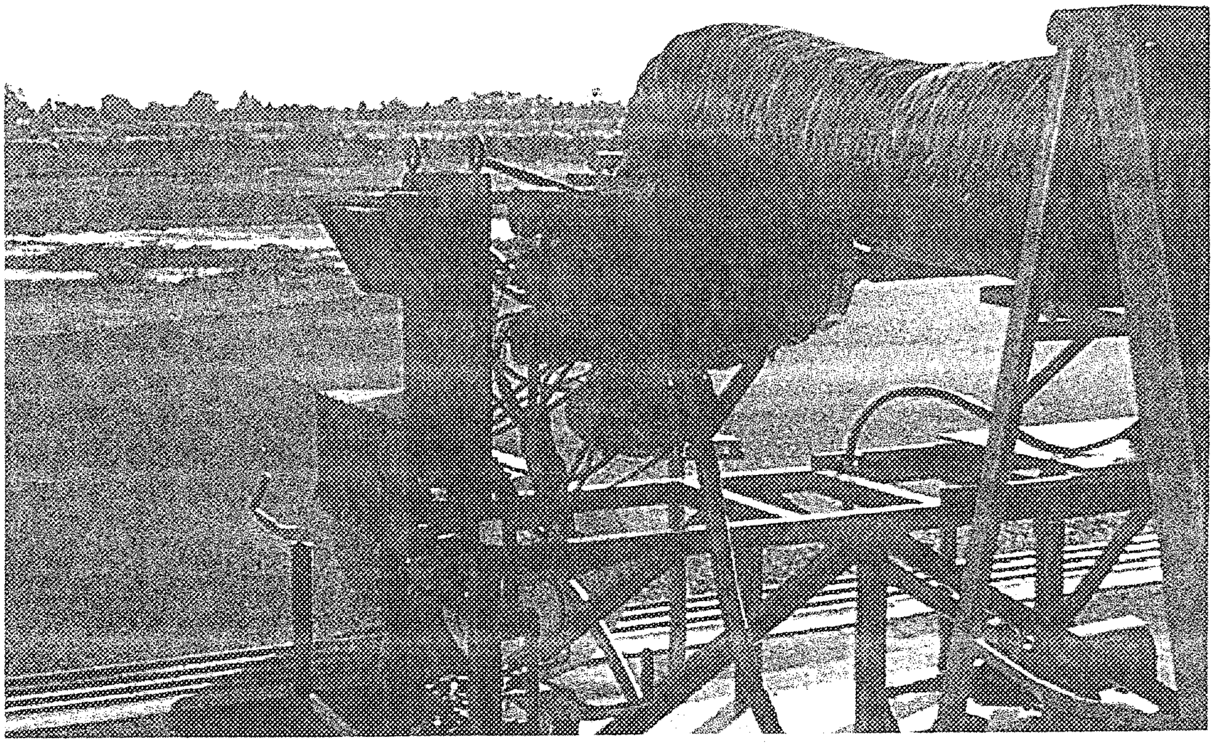


Figure 21.
Engine cooling system of final dynamometer assembly,
with hood fitted directly to engine and connected by flexible ducting

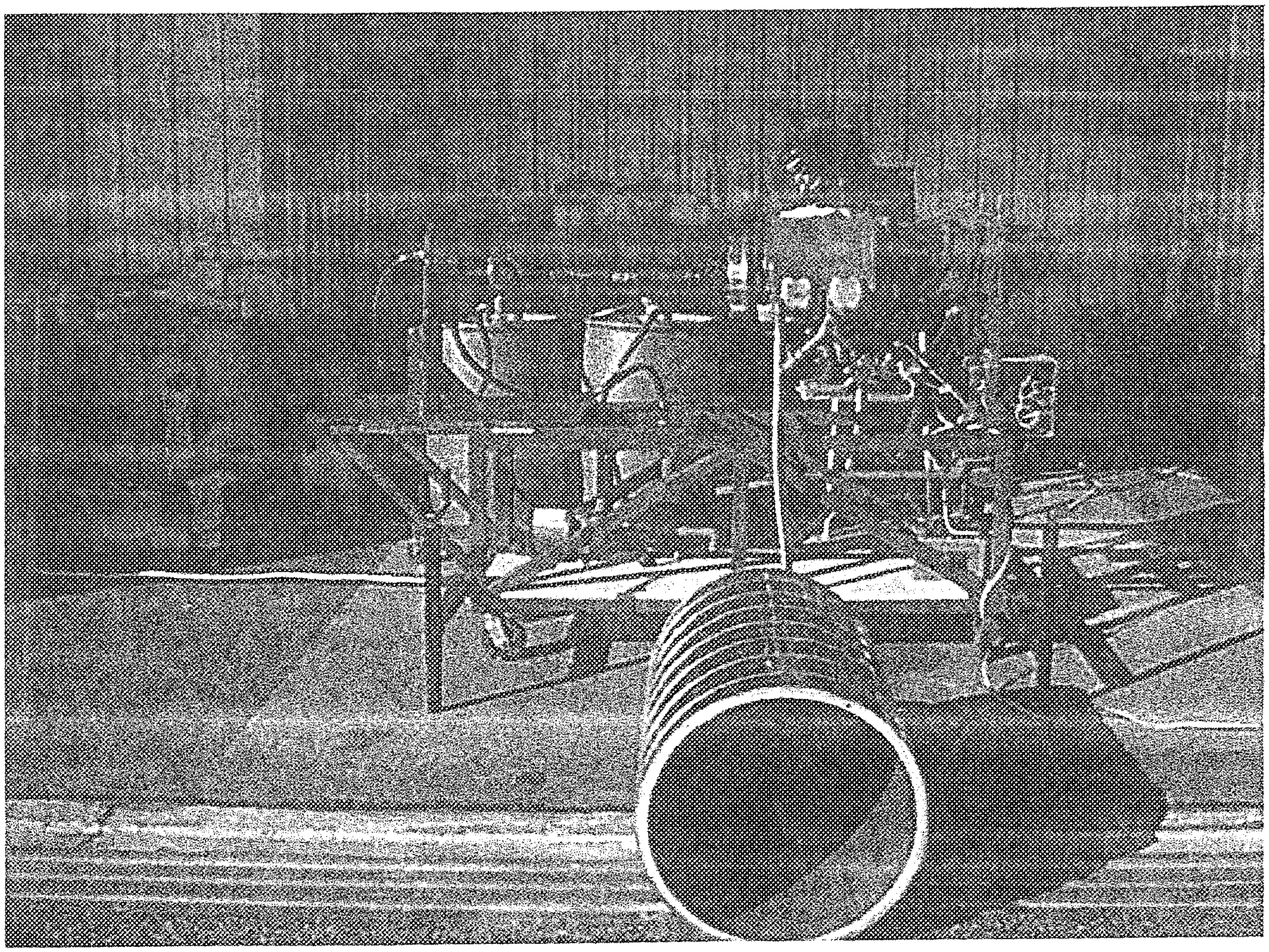
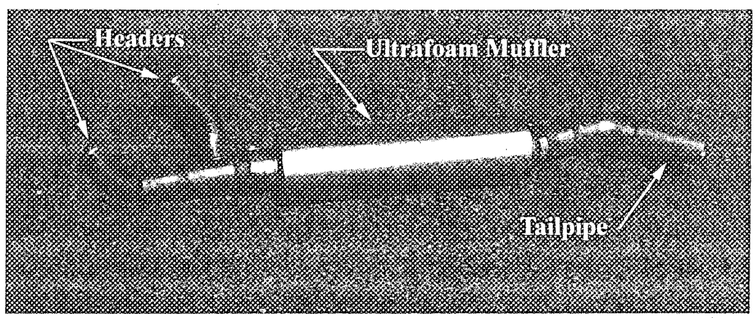
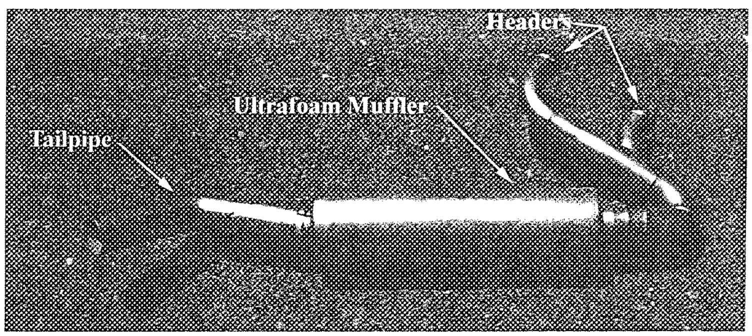


Figure 22.
Acoustic chamber used for mounting of mufflers for dynamometer testing, connected to engine exhaust pipe by flexible stainless-steel pipe

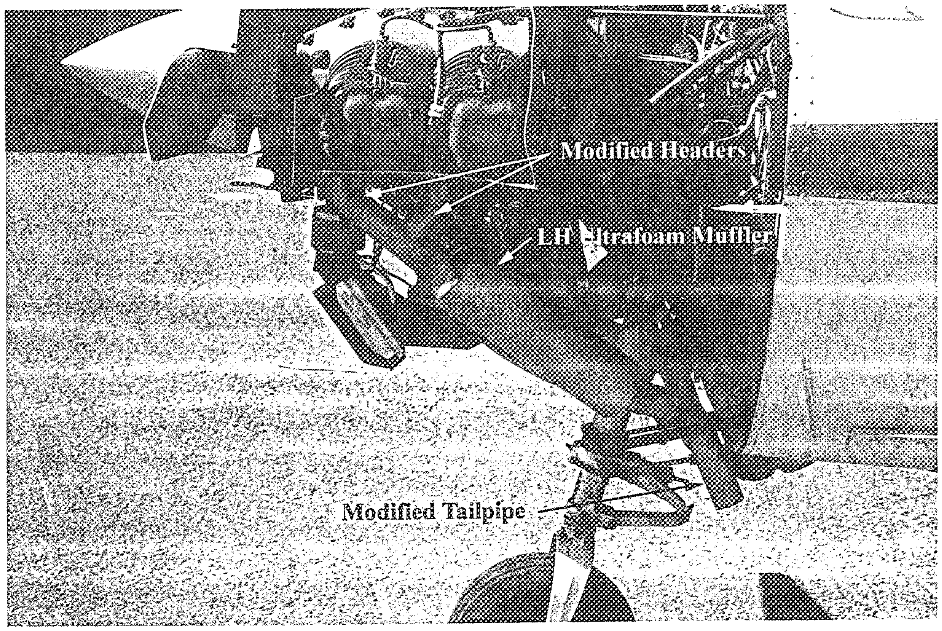


LH Ultrafoam Exhaust System Assembly

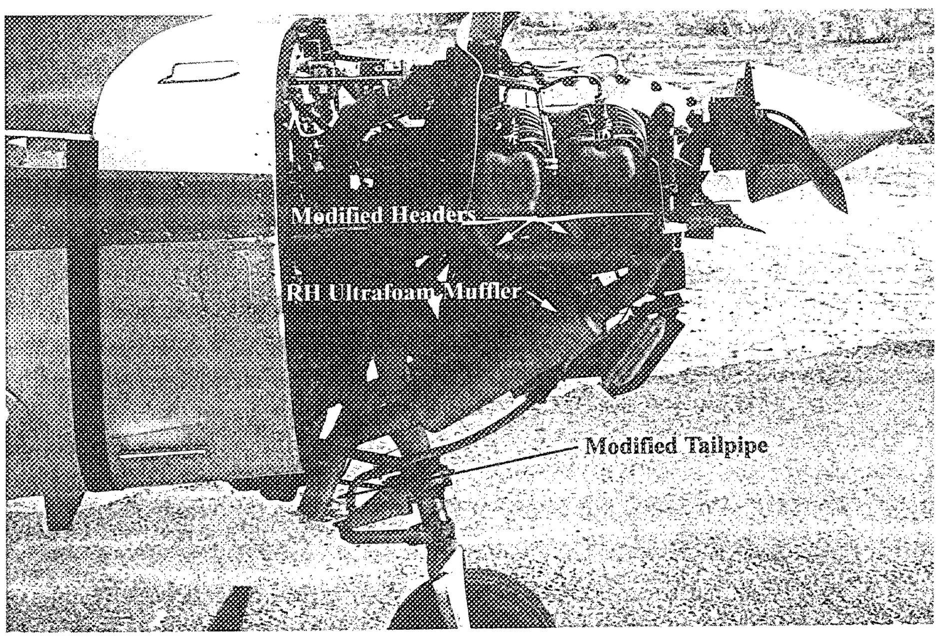


RH Ultrafoam Exhaust System Assembly

Figures 23A-B.
SiC foam-based mufflers used for flight testing on Cessna 150 aircraft
(top: left-side muffler; bottom: right-side muffler)

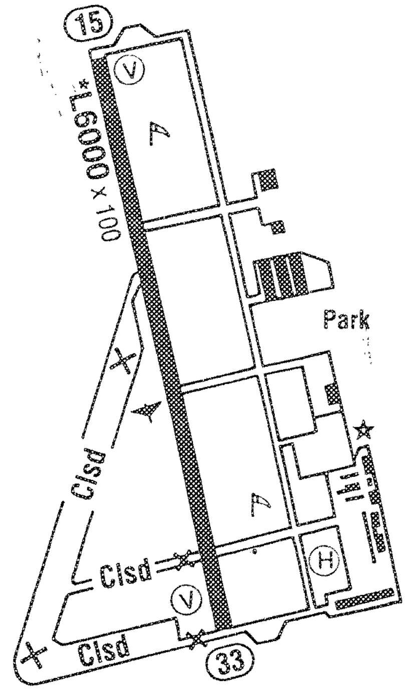


LH Ultrafoam Exhaust System Installation

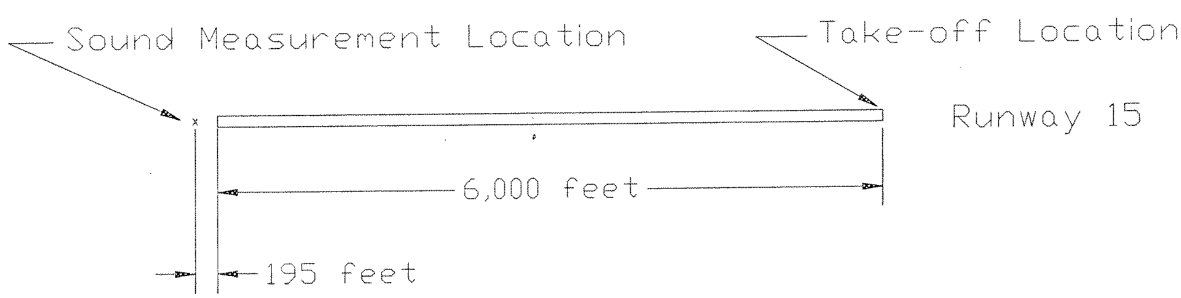


RH Ultrafoam Exhaust System Installation

Figures 24A-B.
SiC foam-based mufflers installed in flight test configuration on Cessna 150 aircraft
(top: left-side installation; bottom: right-side installation)

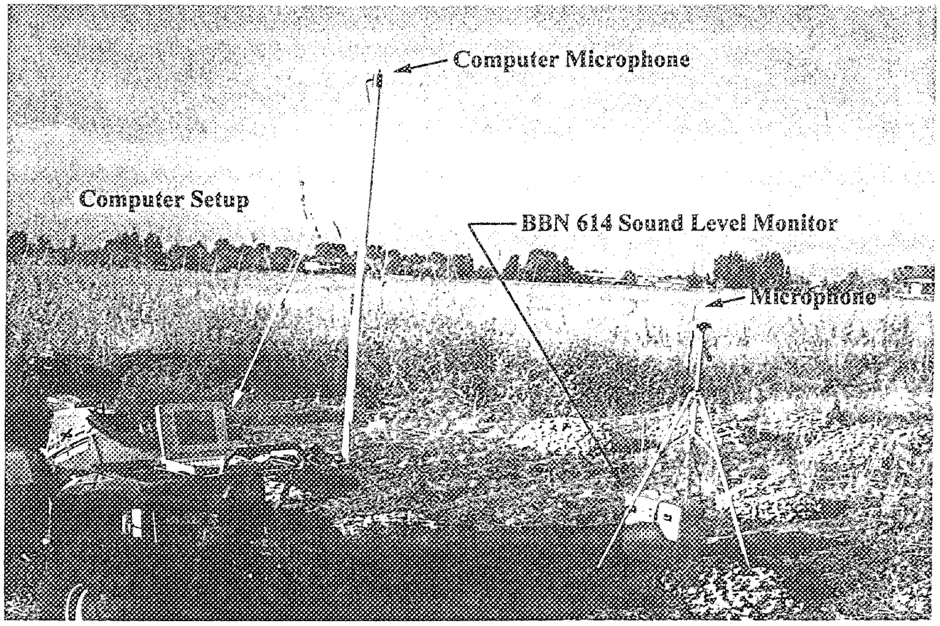


Lincoln Regional Airport, Lincoln CA - Airport Layout



Sound Measurement Location with Reference to Runway

Figure 25.
Schematic of Lincoln Regional Airport runway configuration,
showing placement of noise measurement instrumentation used in flight testing



Data Acquisition Setup at End of Runway 15

View from Sound Measurement Location, 195 Feet from End of Runway

Figures 26A-B.
Noise measurement instrumentation used in flight testing

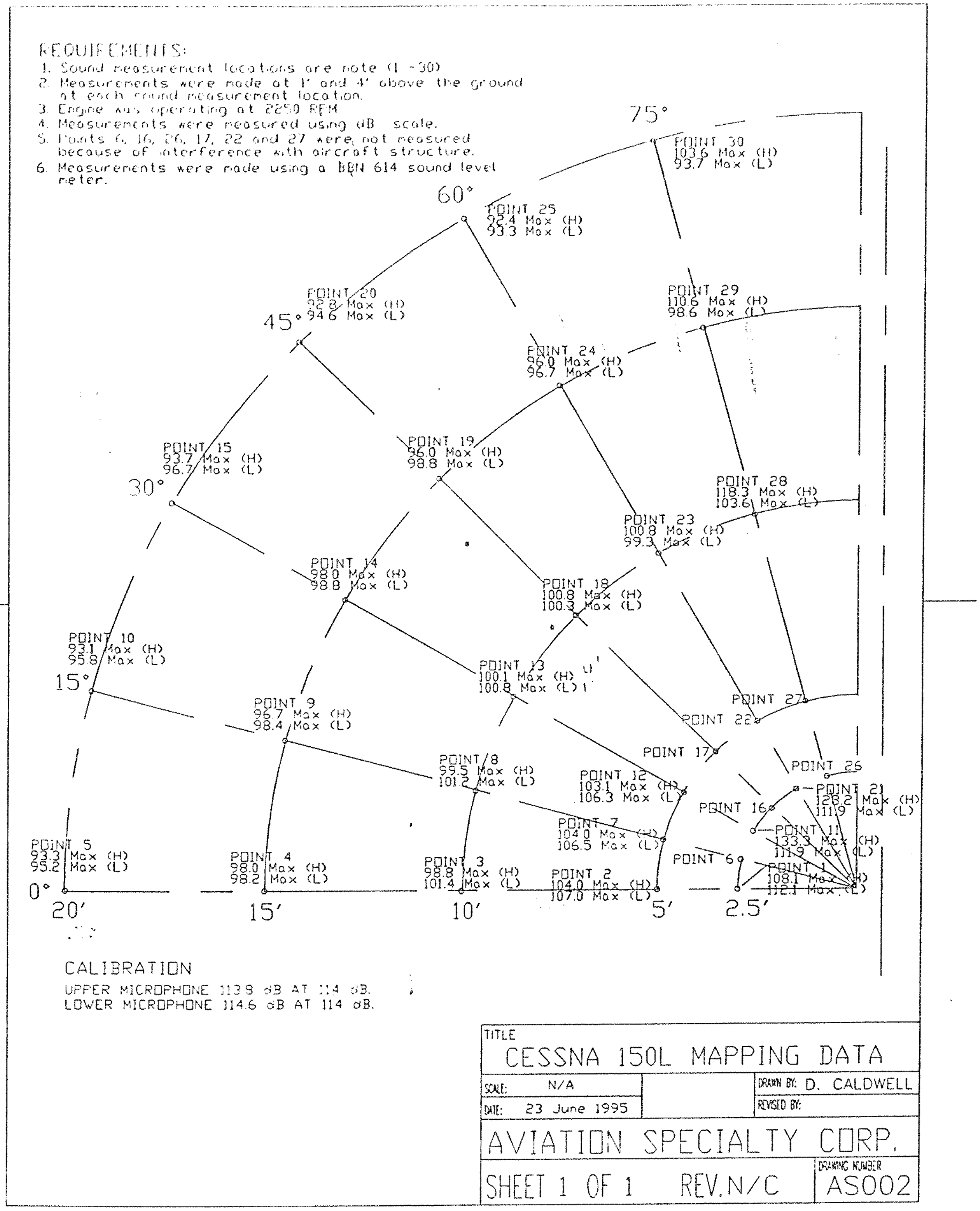


Figure 27.
Non-calibrated external noise level distribution measured from Cessna 150 stock muffler

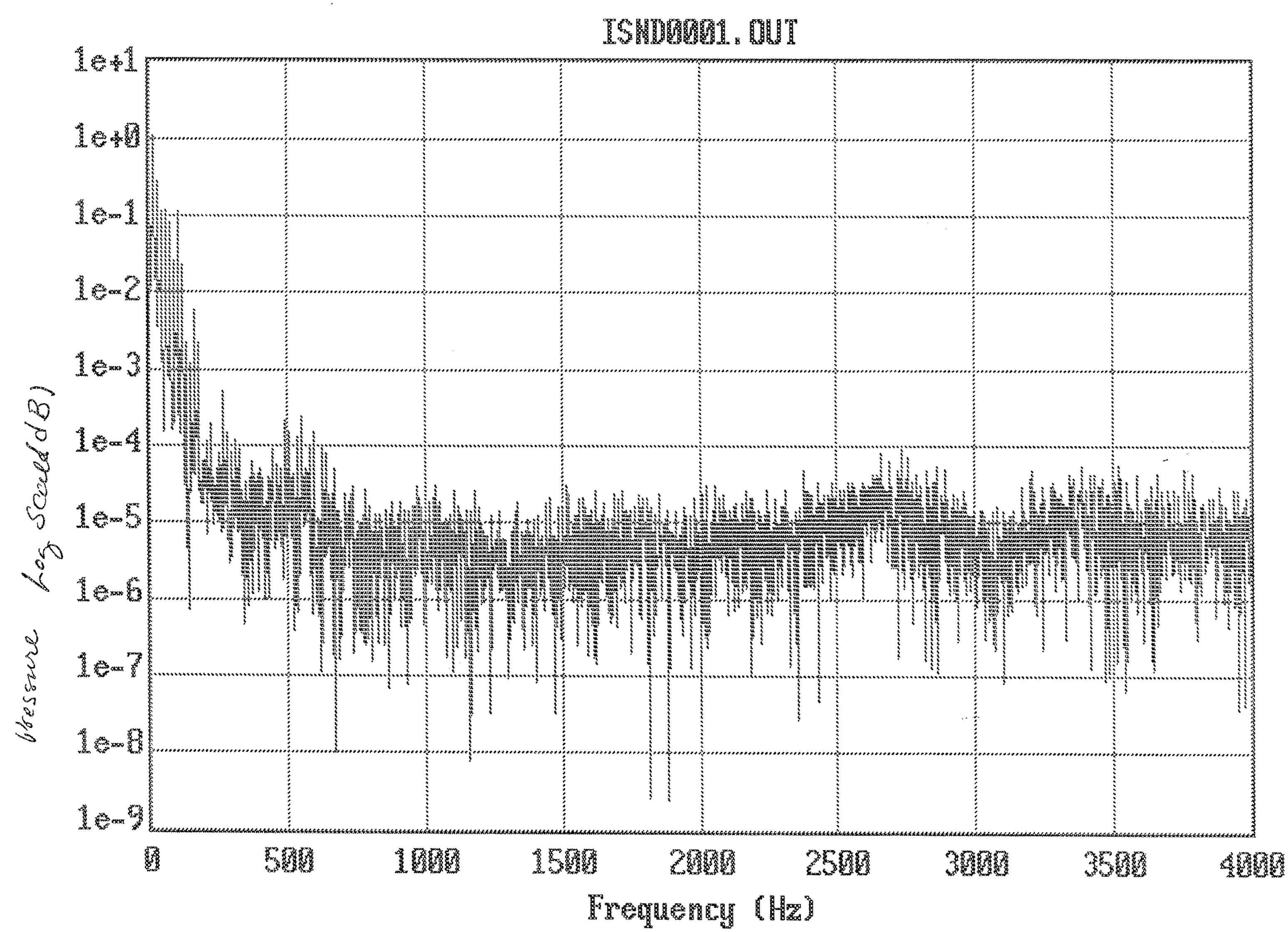


Figure 28.
Overall relative sound pressure level vs. frequency for Continental O-200 engine on Cessna 150 aircraft using stock muffler (measurements performed at 1800-, 2100-, and 2400-rpm engine speeds)

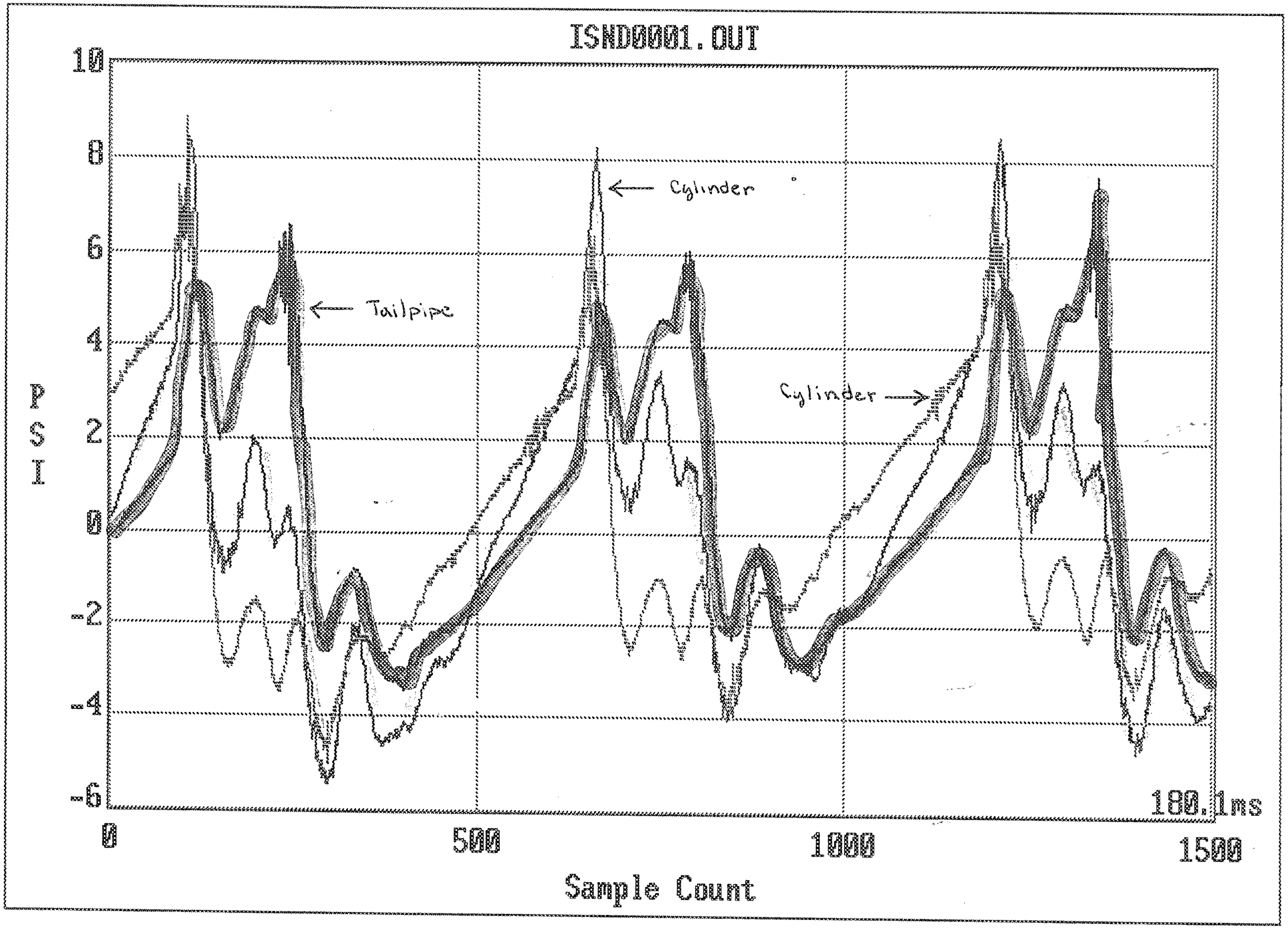


Figure 29.
Sound pressure levels measured in cylinder #1, cylinder #3, and tailpipe of Cessna 150 aircraft using stock muffler

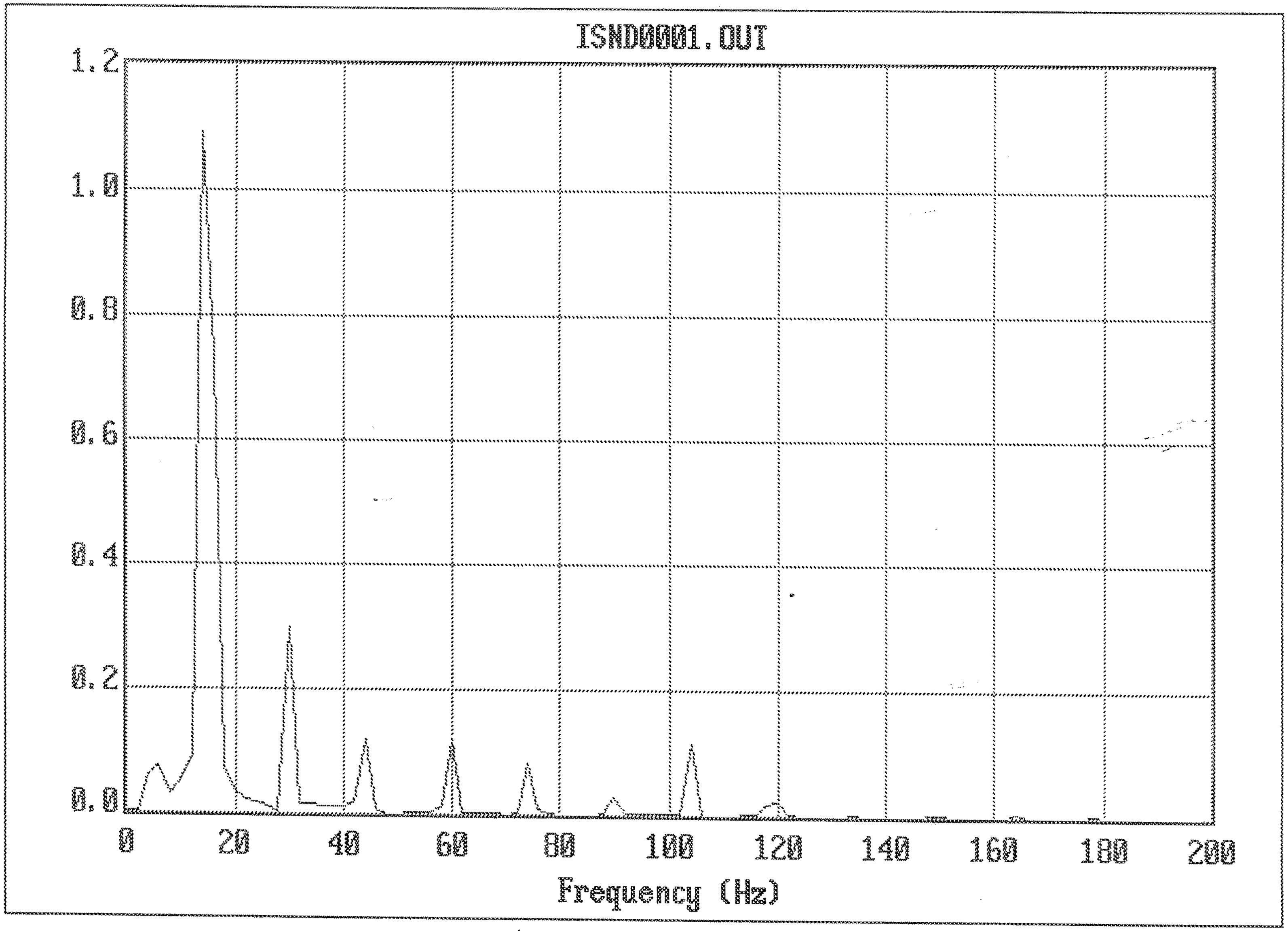


Figure 30.
Relative sound pressure level vs. frequency measured in cylinder #1 of Cessna 150 aircraft using stock muffler

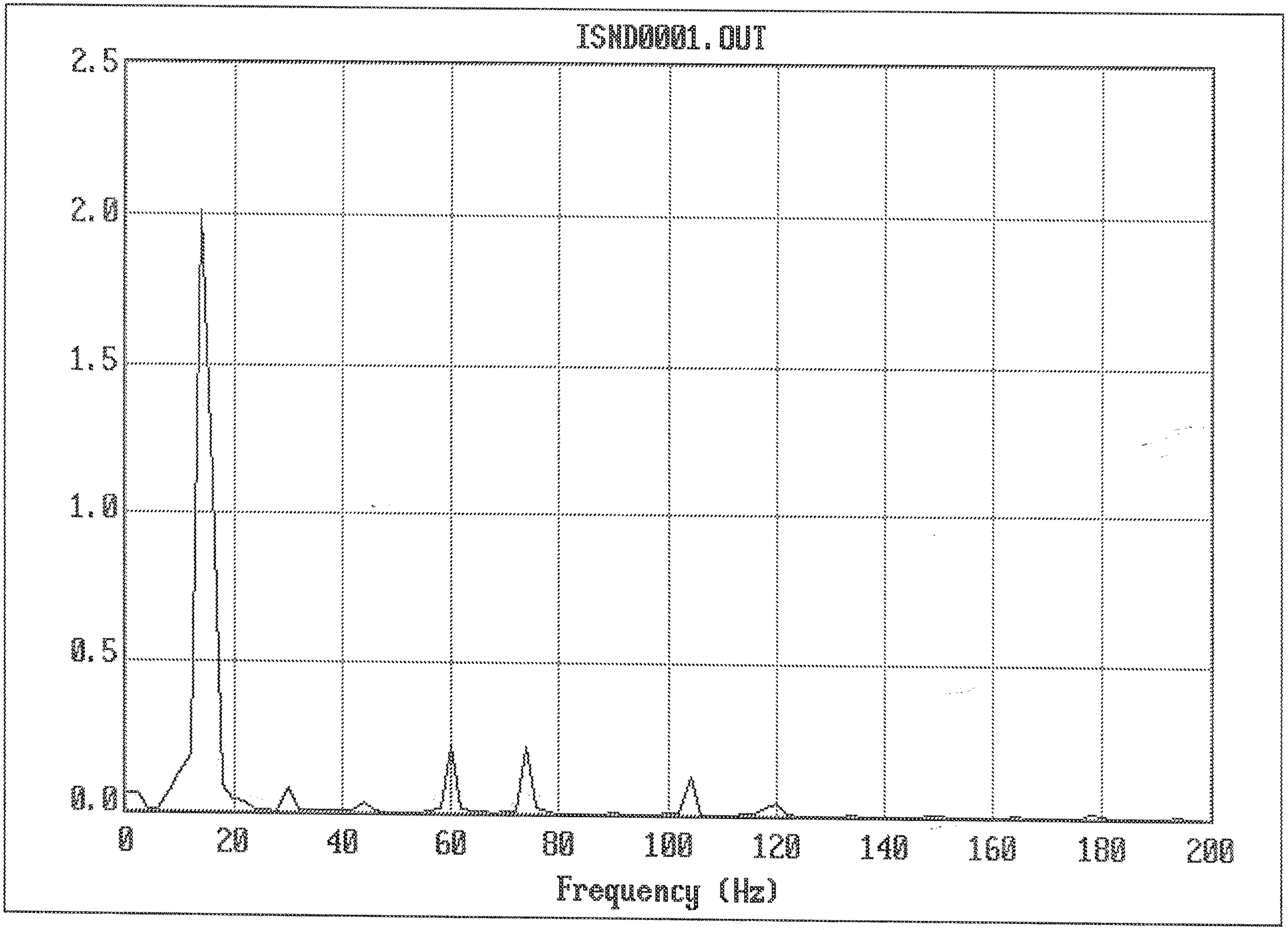


Figure 31.
Relative sound pressure level vs. frequency measured in cylinder #3 of Cessna 150 aircraft using stock muffler

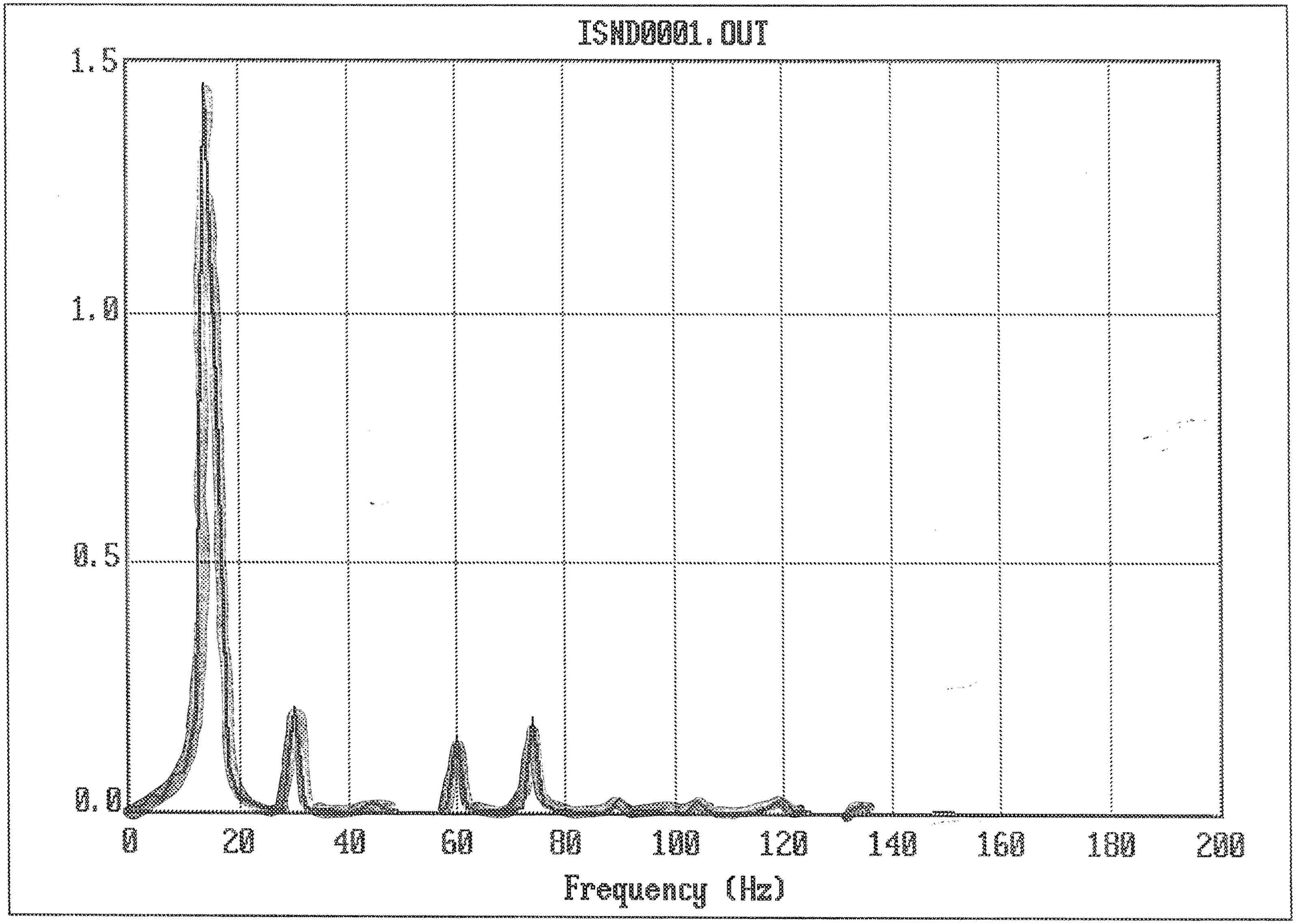


Figure 32.
Relative sound pressure level vs. frequency measured in tailpipe of Cessna 150 aircraft using stock muffler

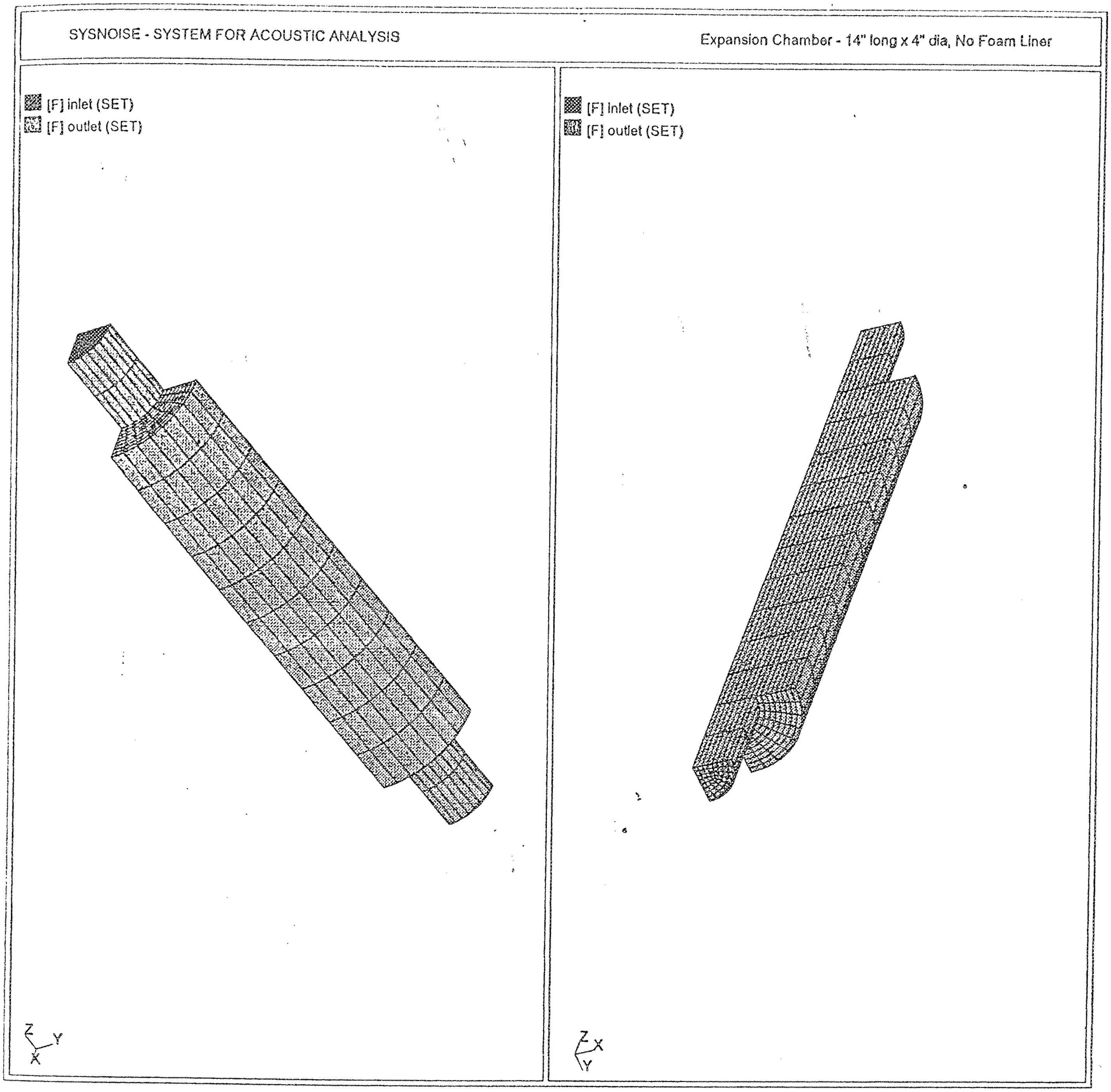


Figure 33.
SYSNOISE model (quarter-section) of baseline 4" OD × 10" long expansion chamber (no SiC foam liner) with 2" diameter × 2" long inlet and outlet pipes

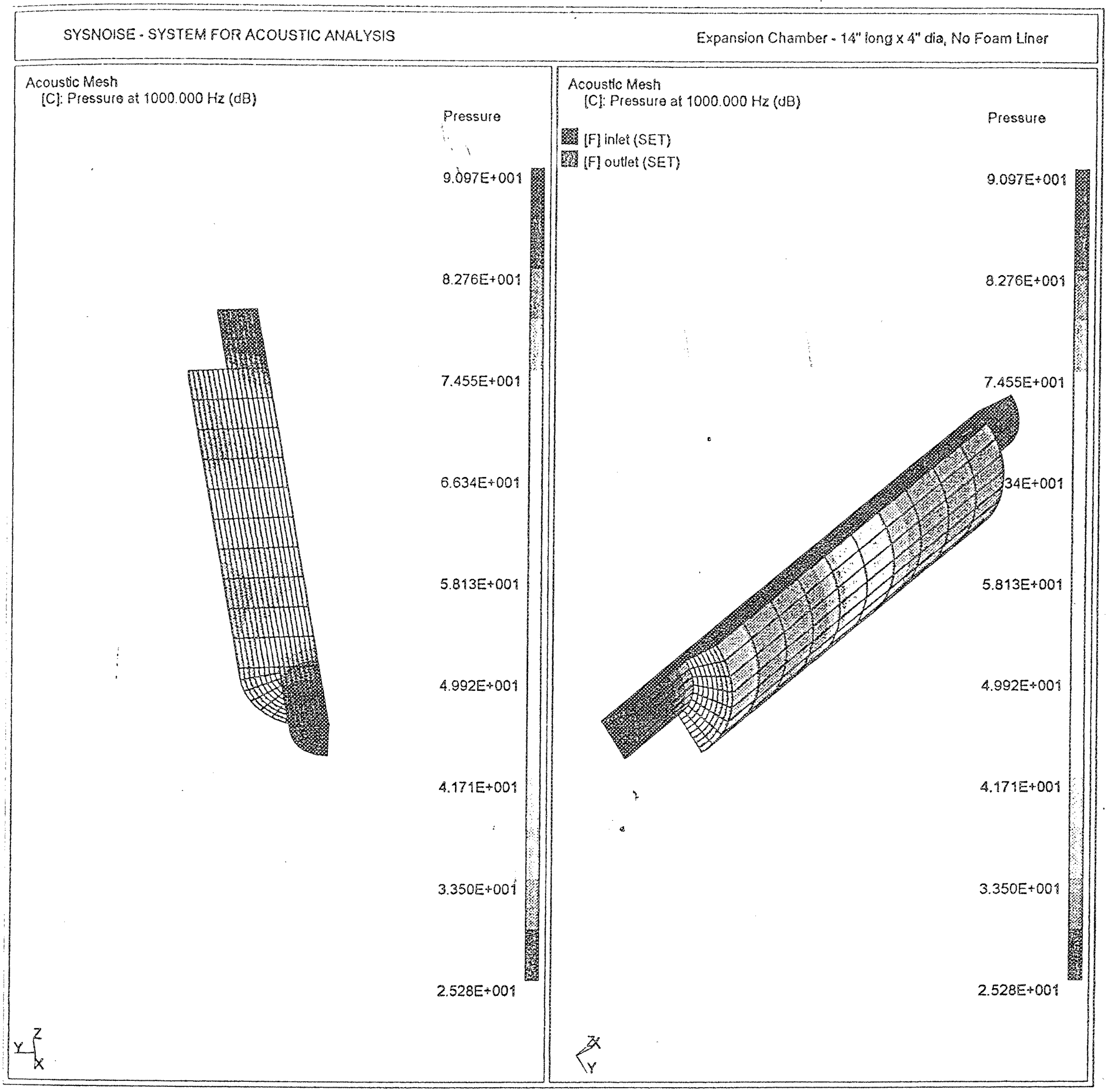


Figure 34.
SYSNOISE model (quarter-section) of sound pressure level distribution inside baseline expansion chamber (inlet is at lower end of chamber in both views)

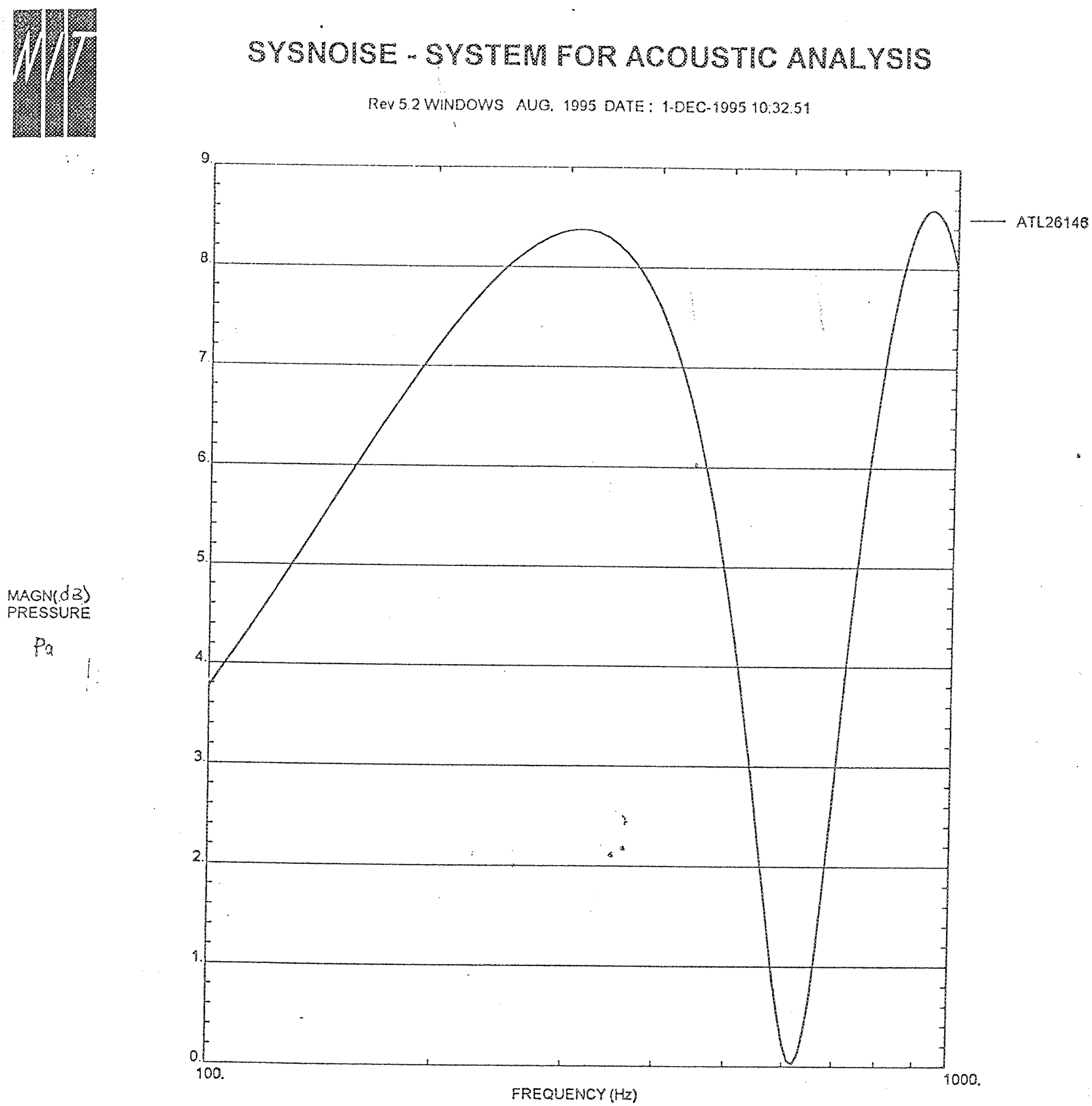


Figure 35.
Transmission loss vs. frequency for baseline expansion chamber

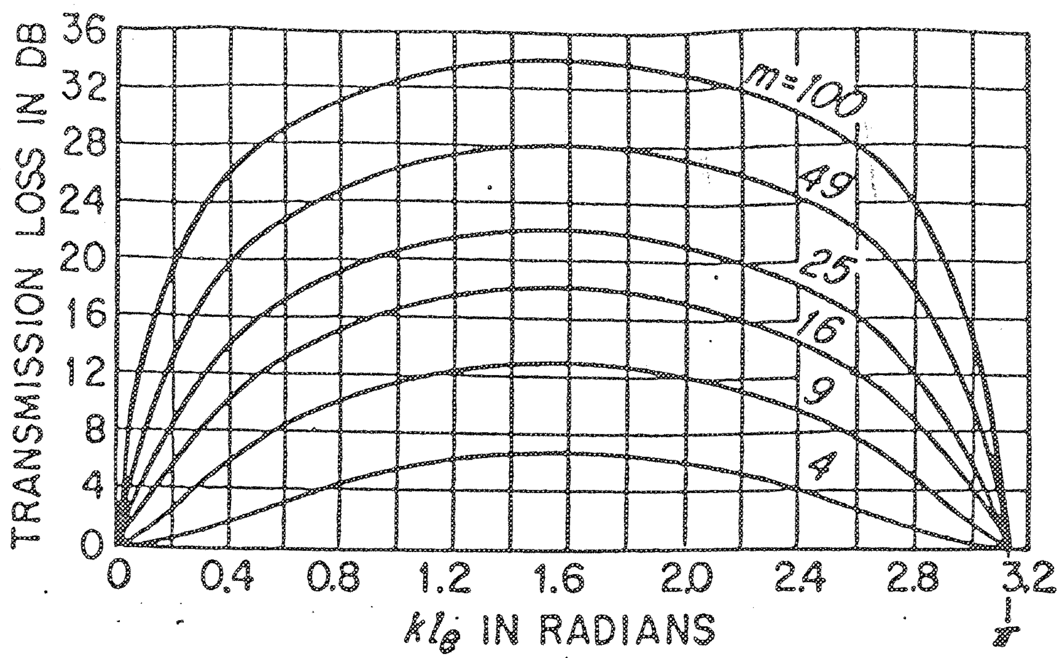


Figure 36.
Transmission loss for a single expansion chamber as a function of length for several expansion ratio values (as calculated from plane-wave theory)

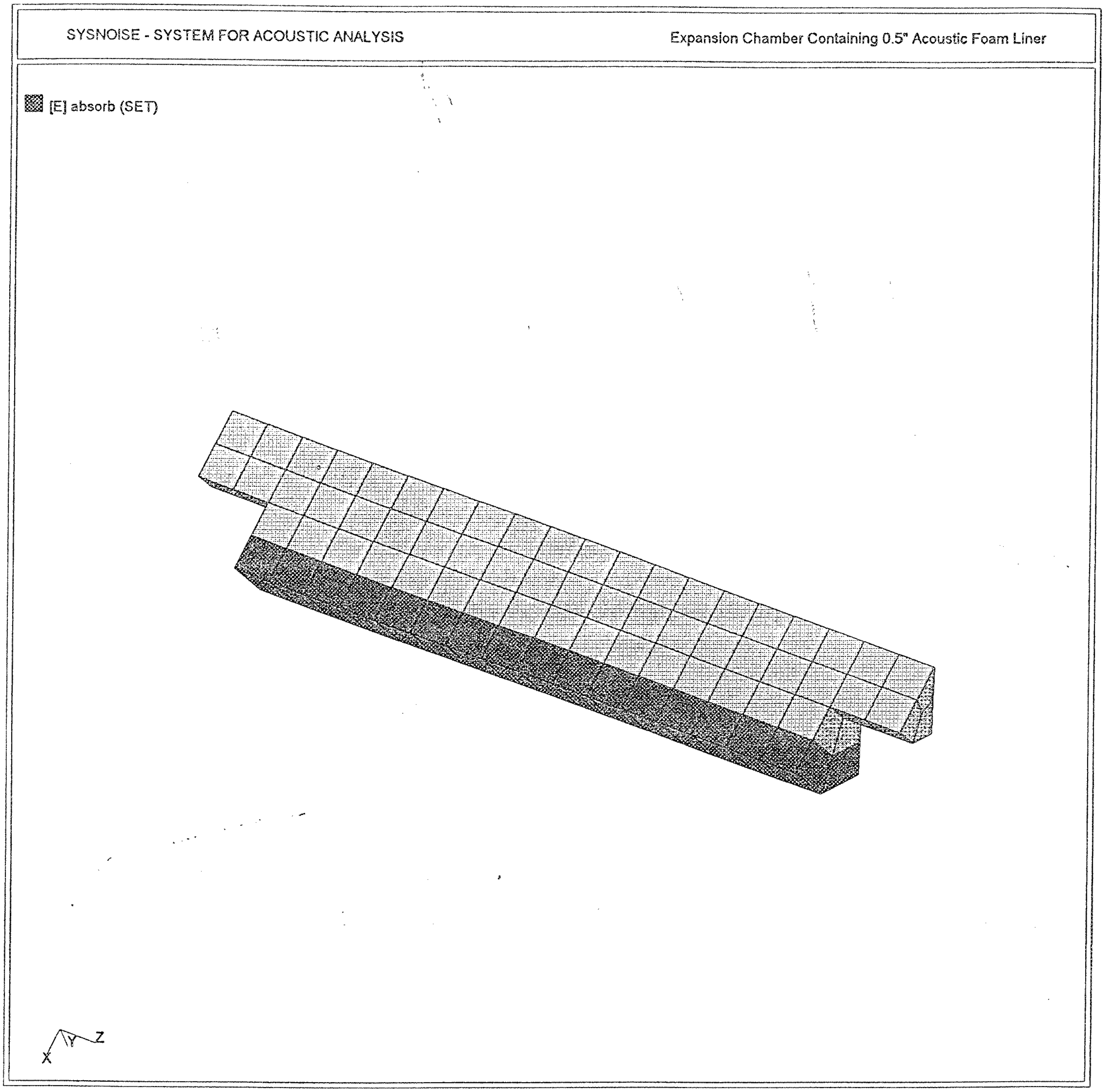


Figure 37.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber with 0.5" thick SiC foam liner

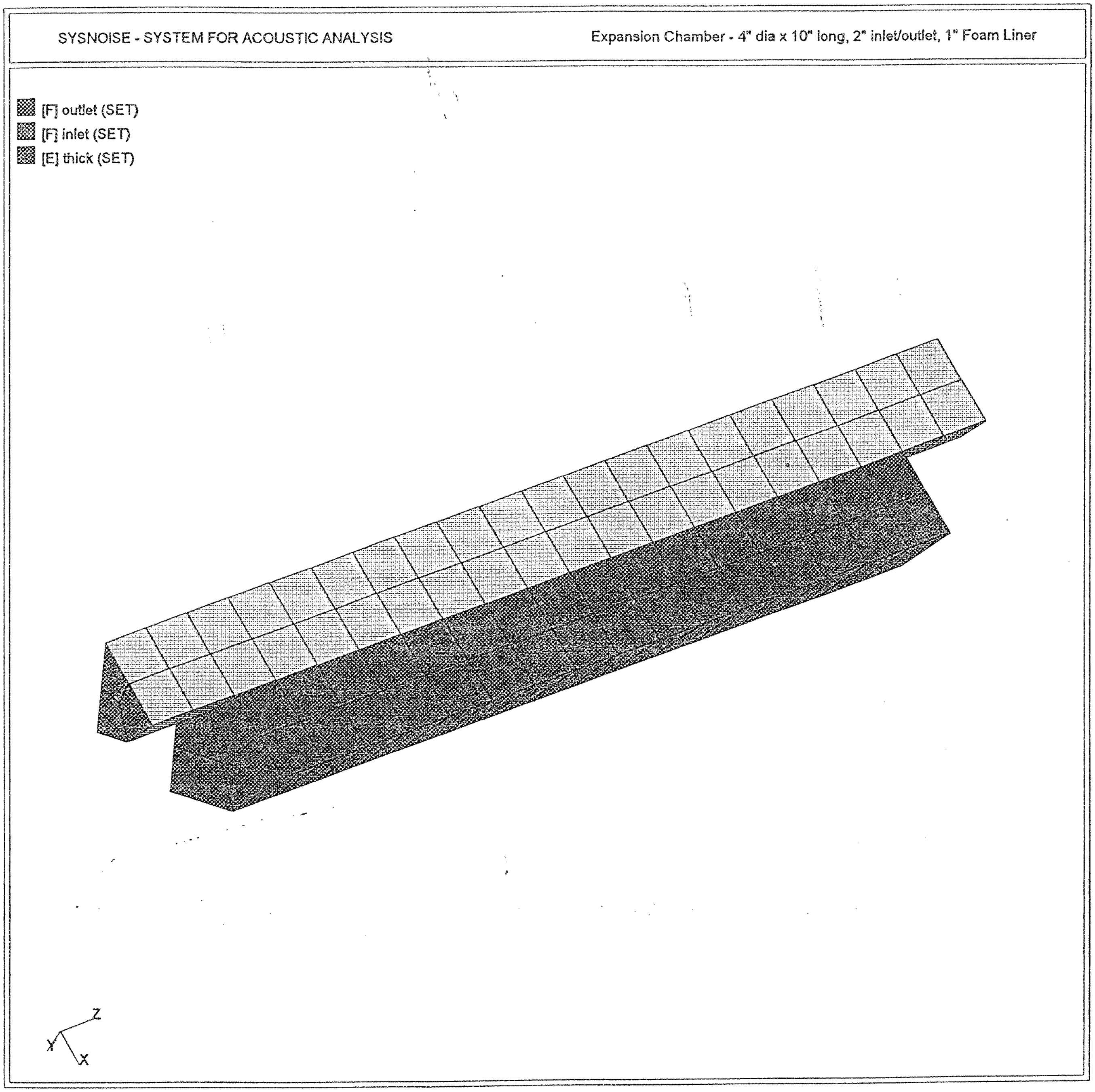


Figure 38.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber with 1" thick SiC foam liner

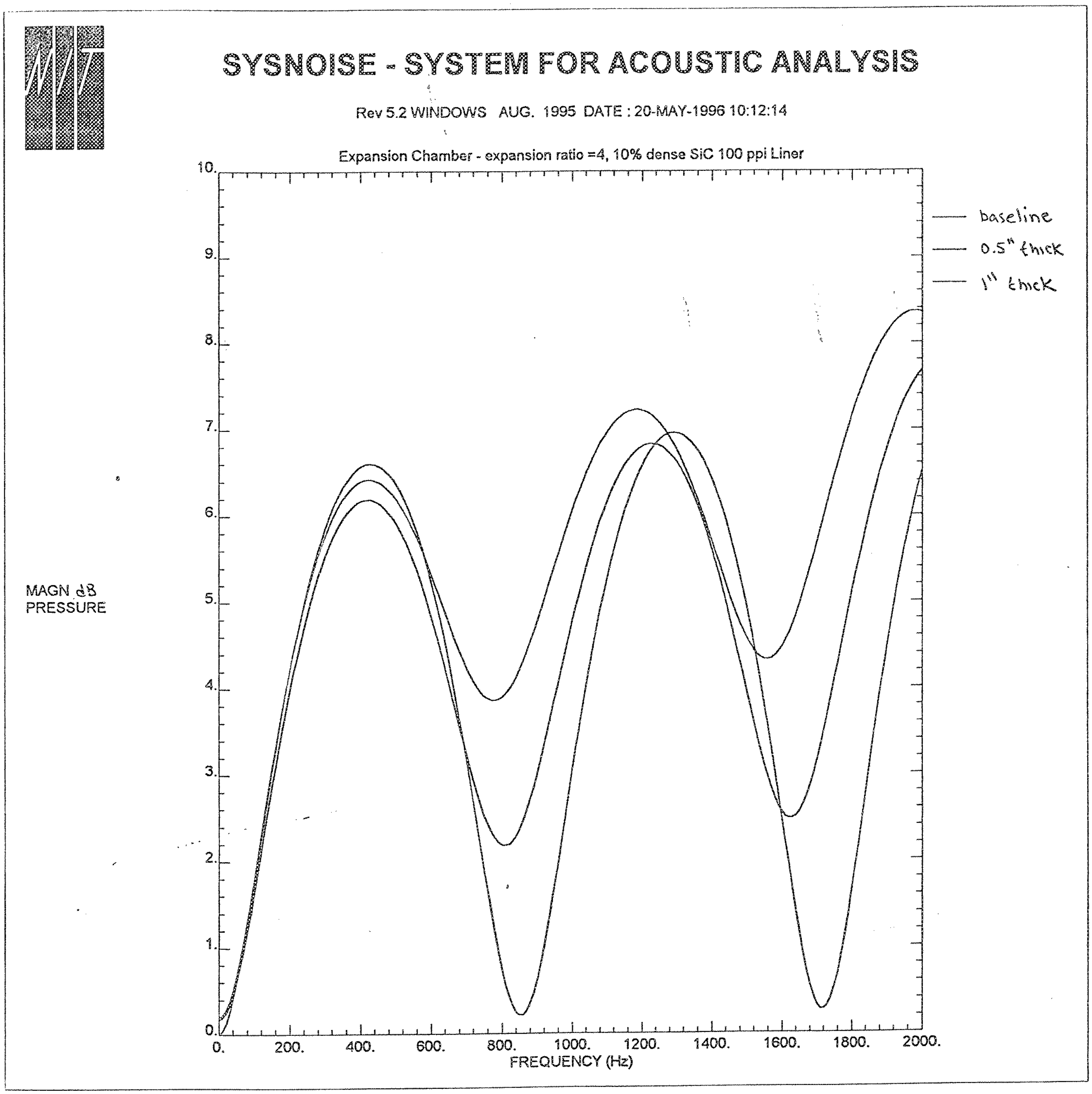


Figure 39.
Transmission loss vs. frequency for expansion chambers
with 100-ppi, 10% dense SiC foam liners of various thicknesses

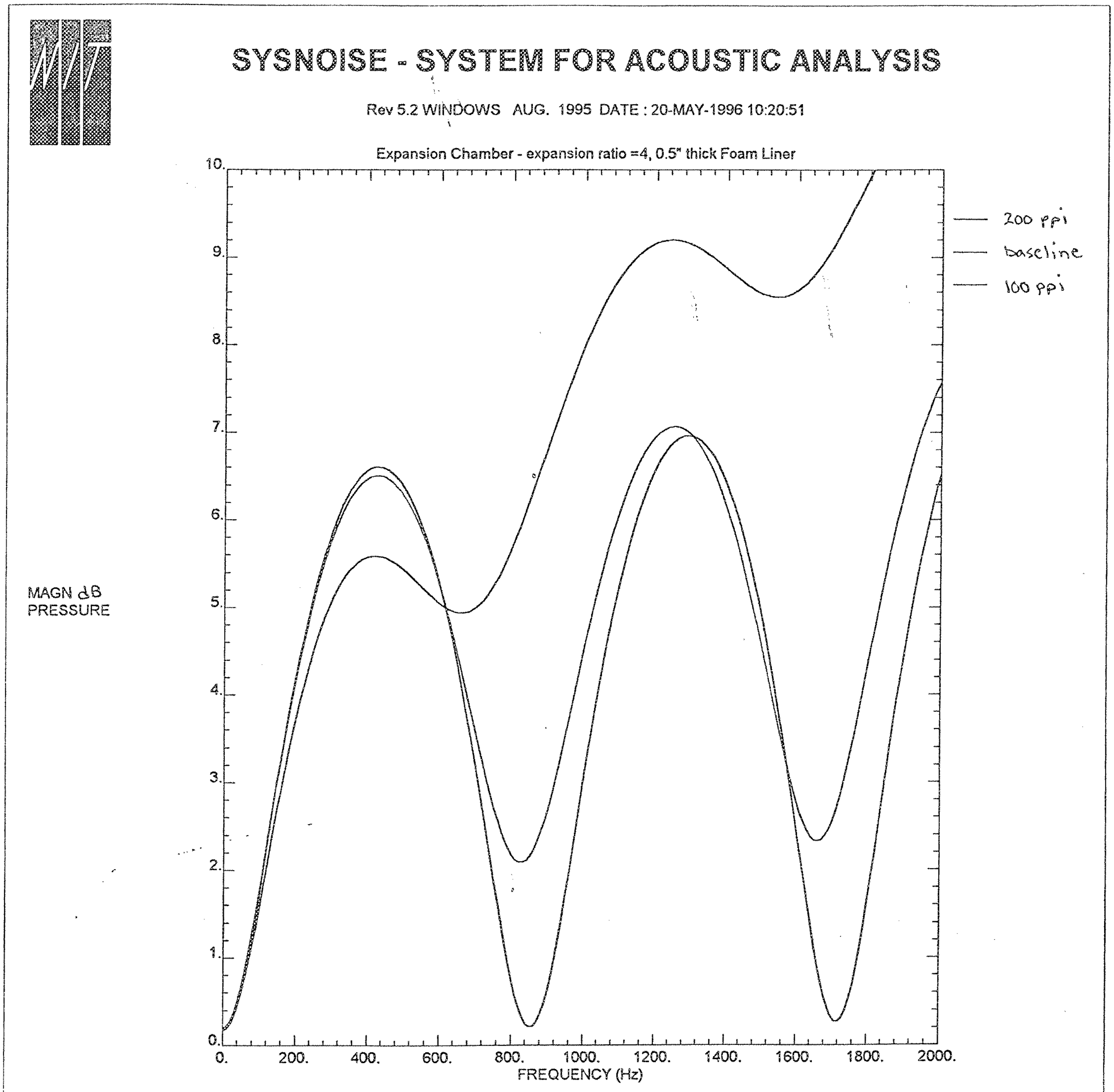


Figure 40.
Transmission loss vs. frequency for expansion chambers with 0.5" thick RVC foam liners of various pore sizes

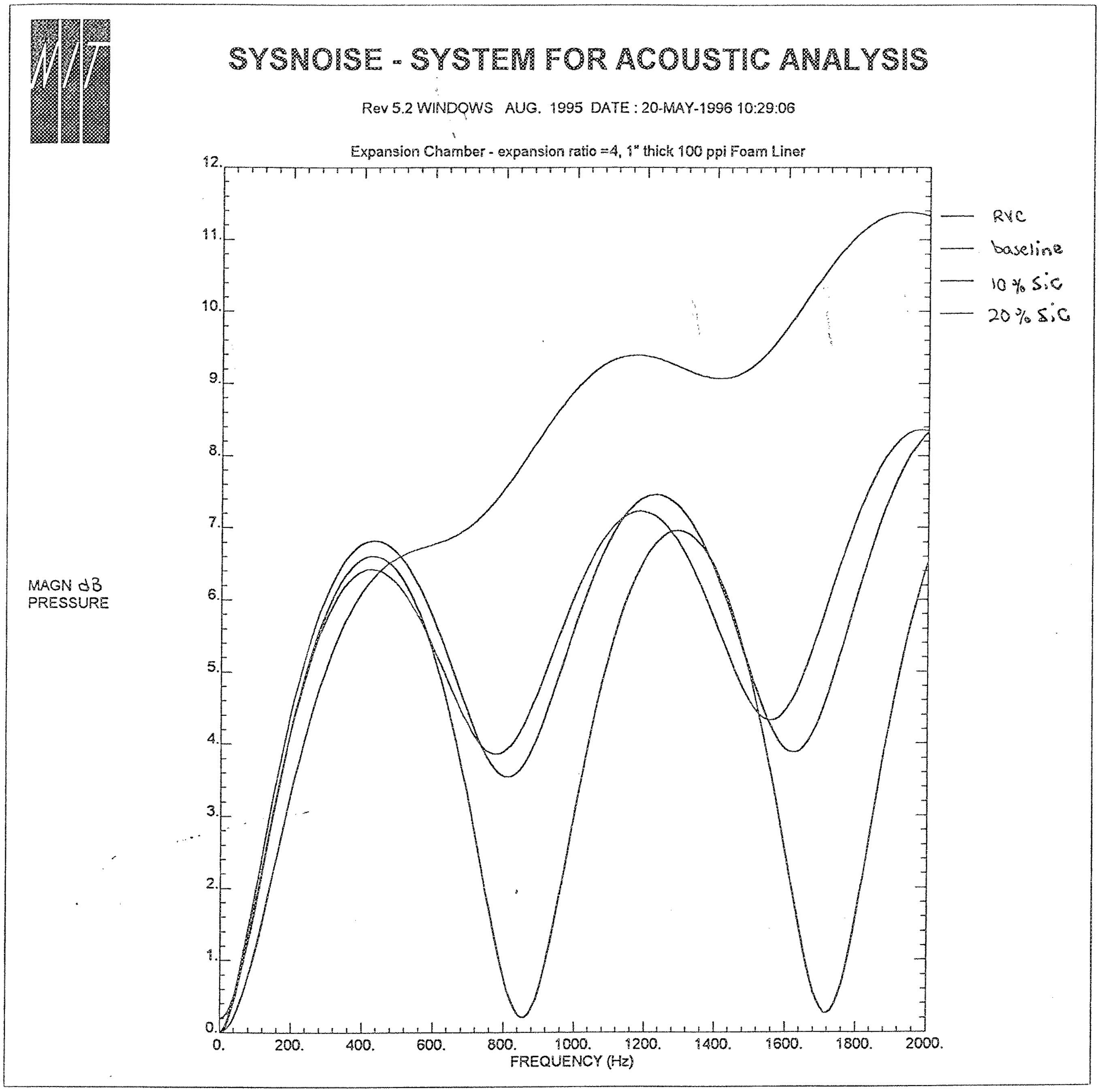


Figure 41.
Transmission loss vs. frequency for expansion chambers with 1" thick, 100-ppi SiC foam liners of various densities or 1" thick, 100-ppi RVC foam liner

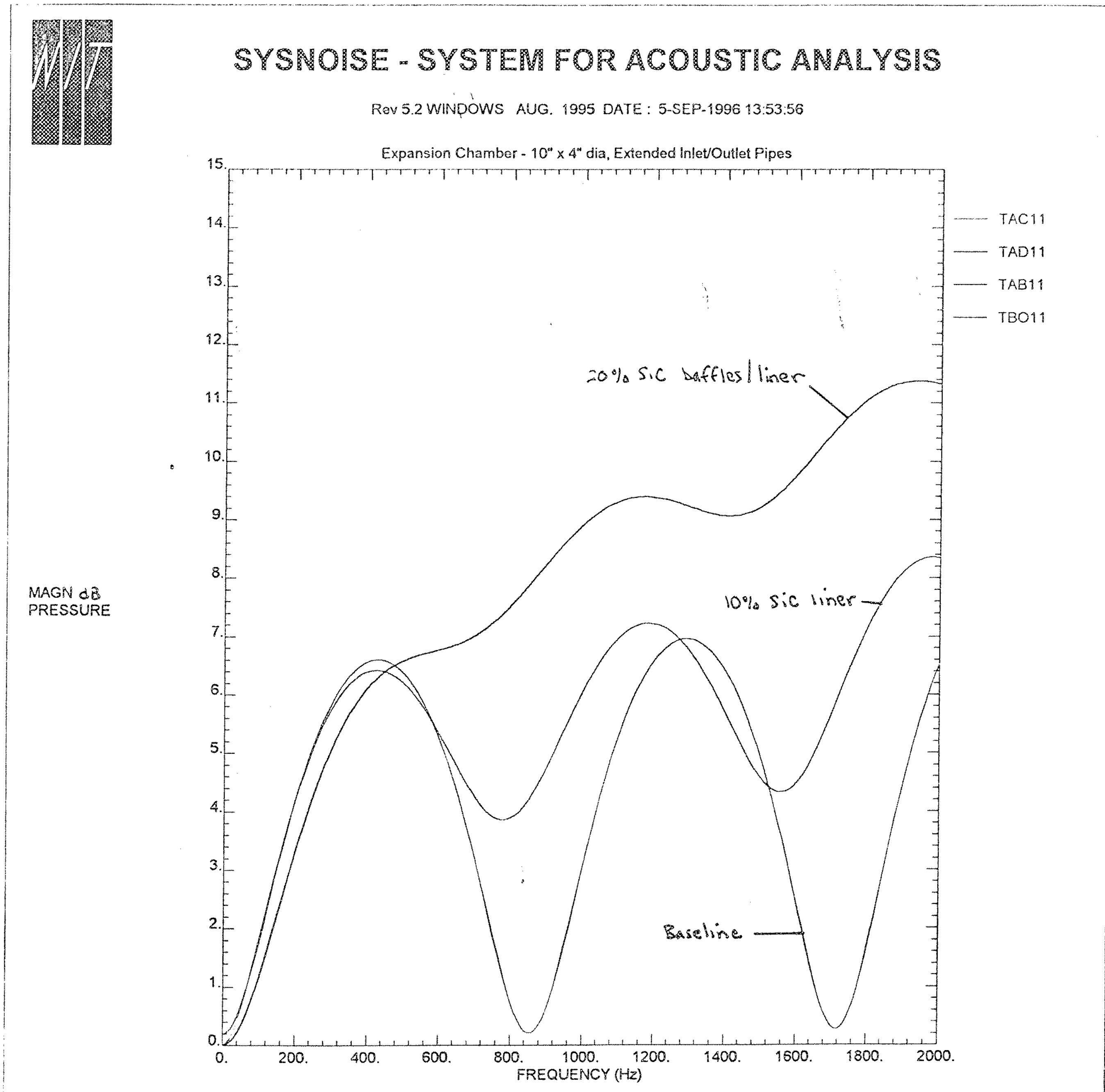


Figure 42.
Transmission loss vs. frequency for expansion chambers with 20% dense SiC foam baffles and liner or 10% dense SiC foam liner only

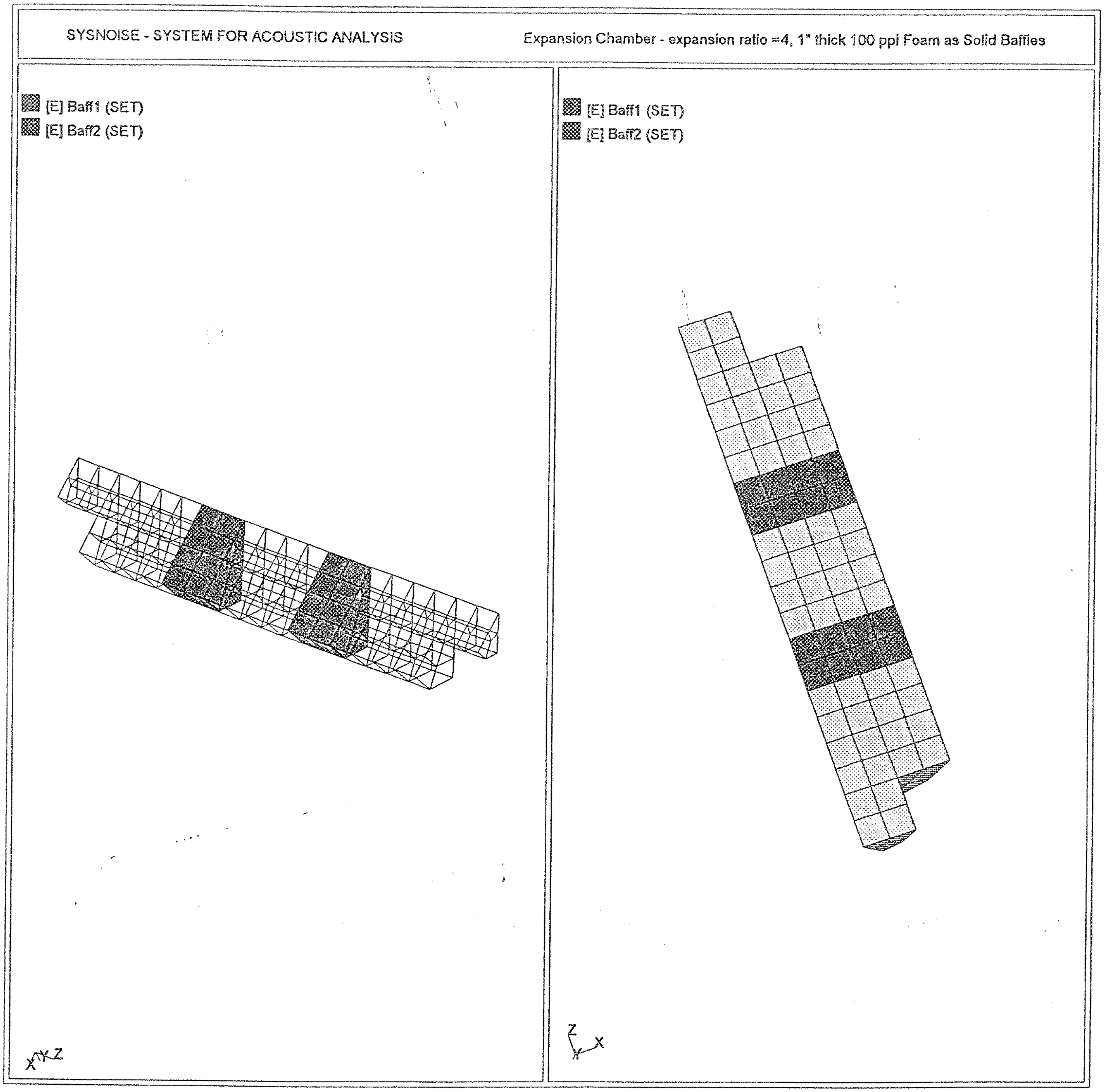


Figure 43.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber
with 1" thick, 100-ppi SiC foam baffles

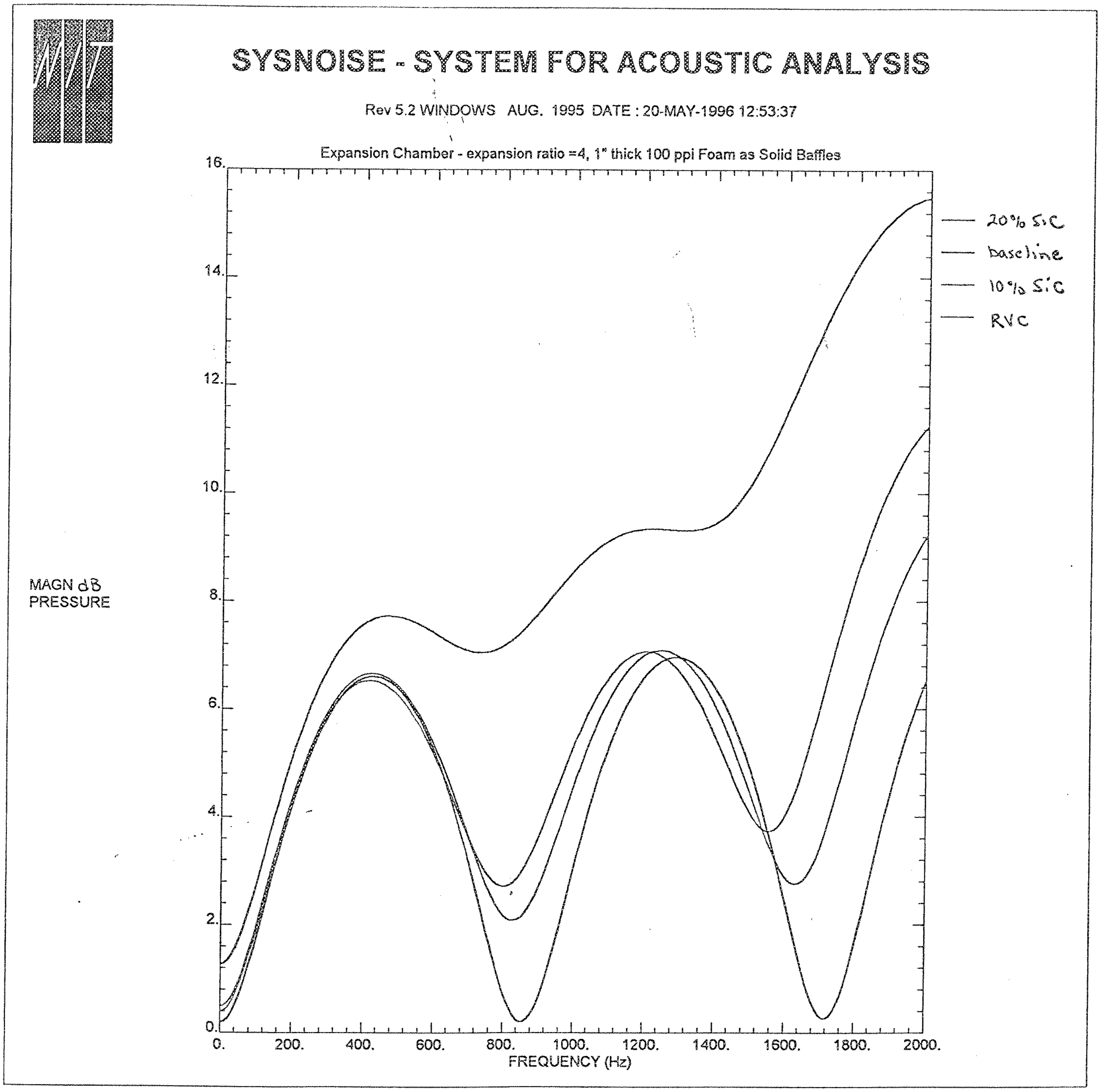


Figure 44.
Transmission loss vs. frequency for expansion chambers
with 1" thick, 100-ppi SiC foam baffles of various densities

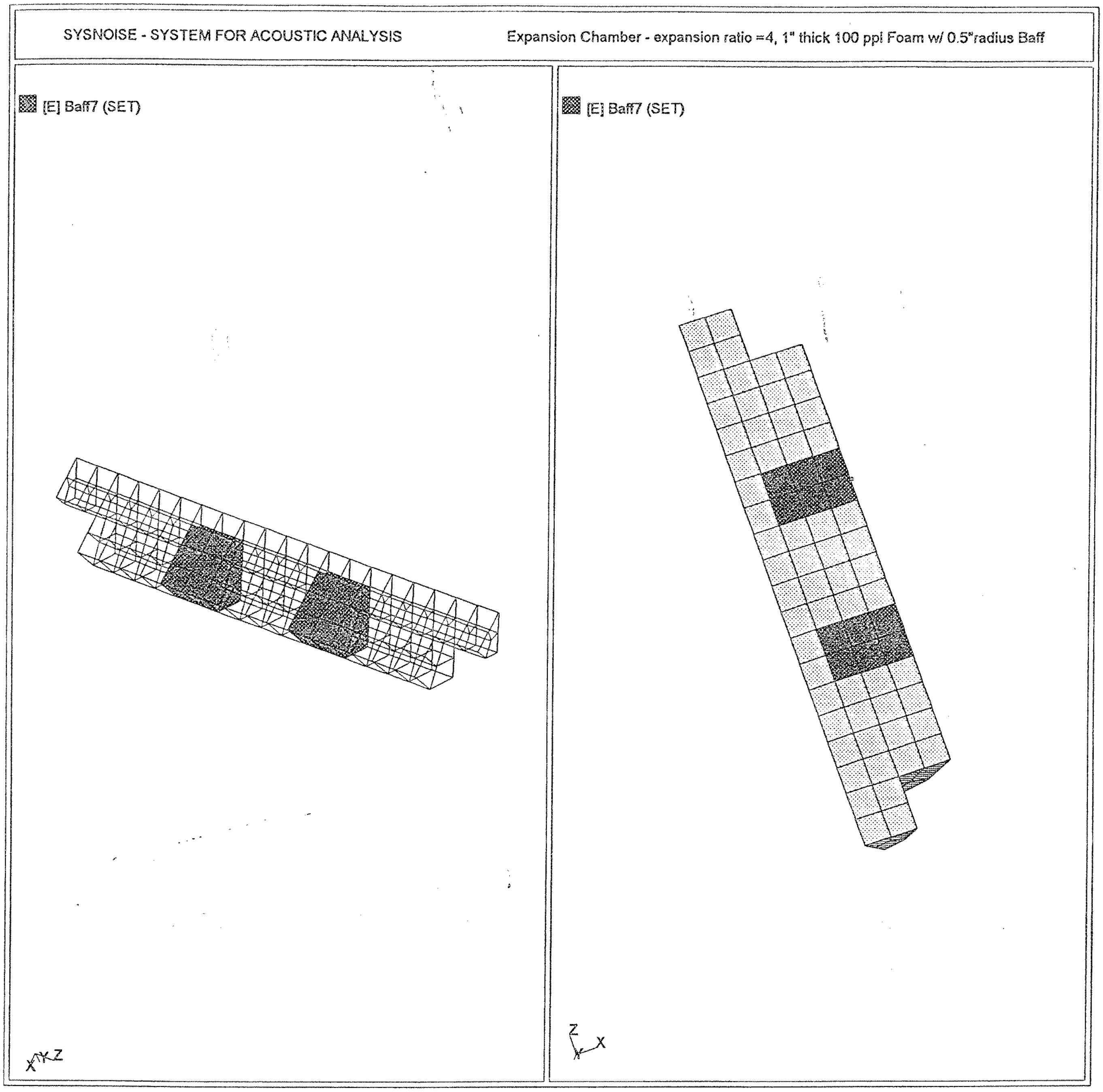


Figure 45.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber with 1" diameter, 1" thick, 100-ppi SiC foam donut baffles

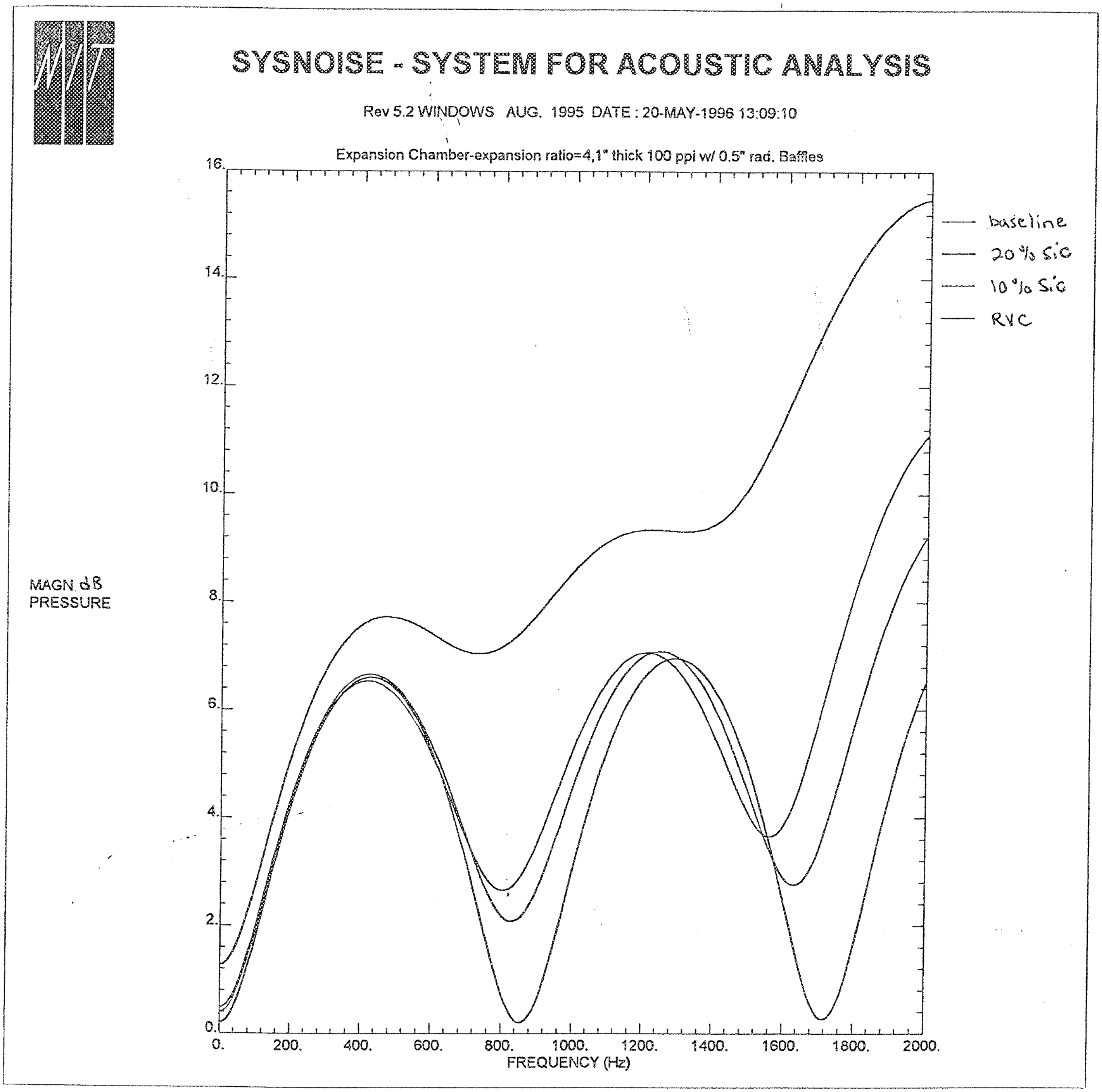


Figure 46.
Transmission loss vs. frequency for expansion chambers with 1" diameter, 1" thick, 100-ppi RVC and SiC foam donut baffles of various densities

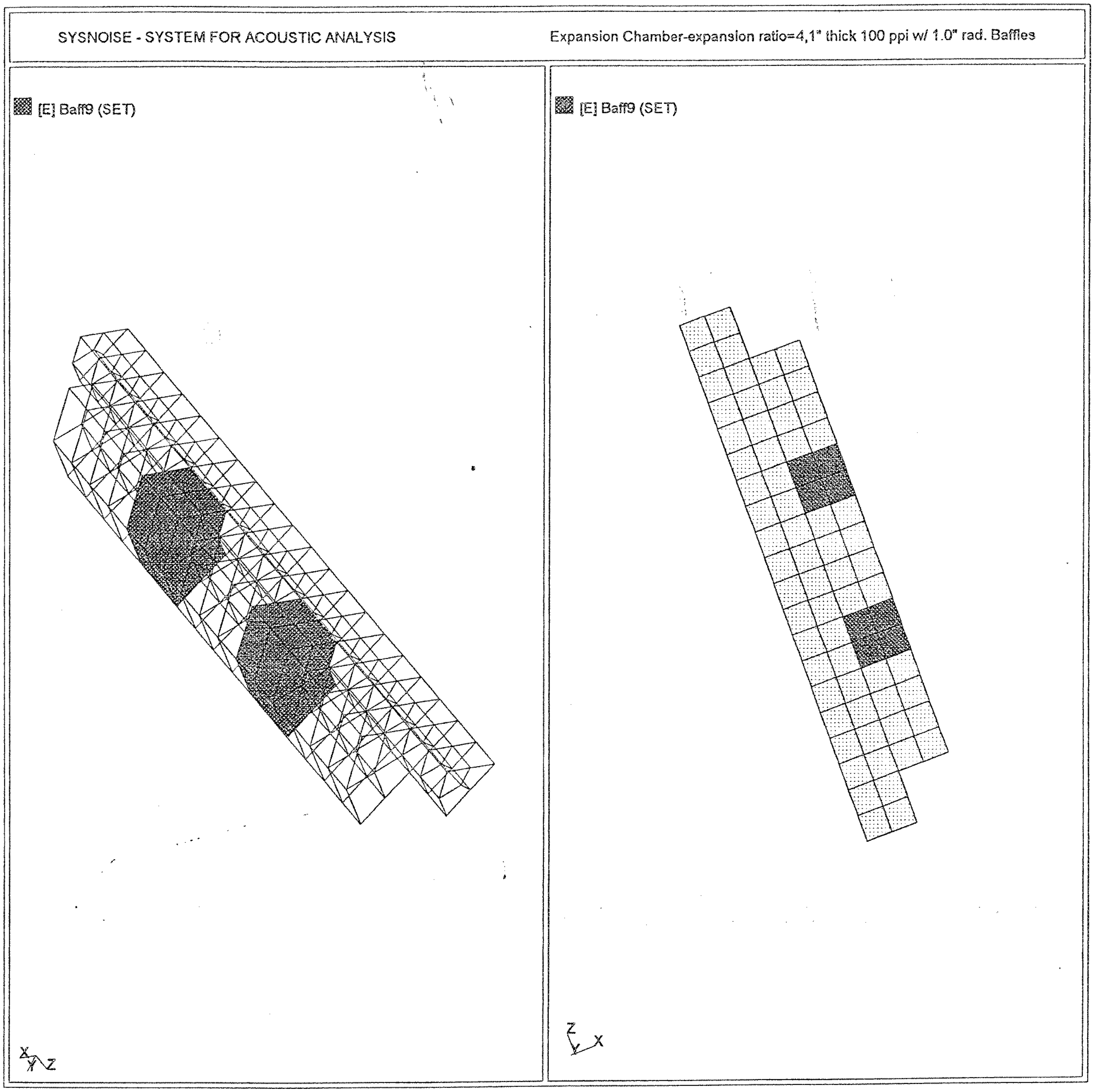


Figure 47.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber with 2" diameter, 1" thick, 100-ppi SiC foam donut baffles

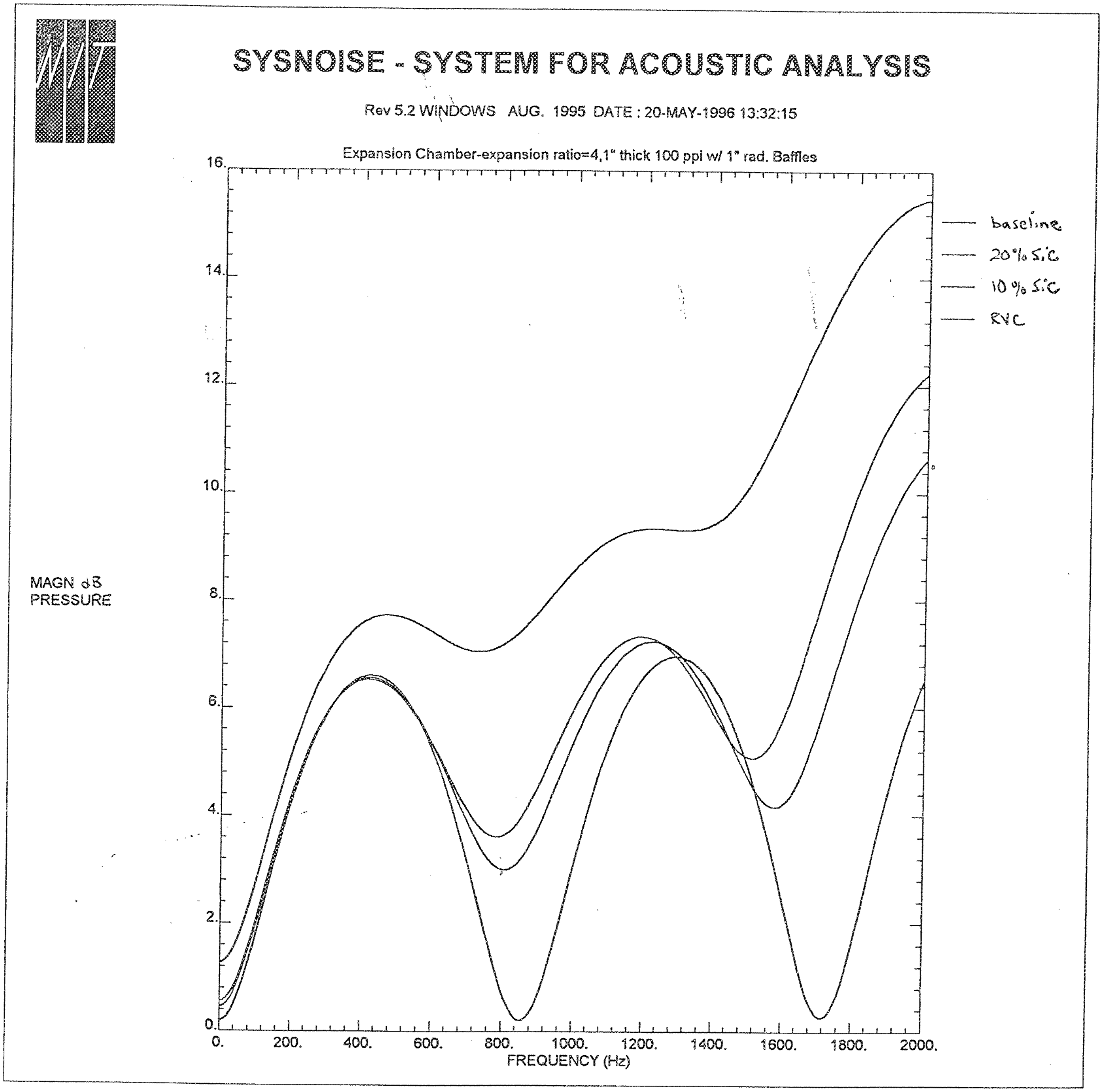


Figure 48.
Transmission loss vs. frequency for expansion chambers with 2" diameter, 1" thick, 100-ppi RVC and SiC foam donut baffles of various densities

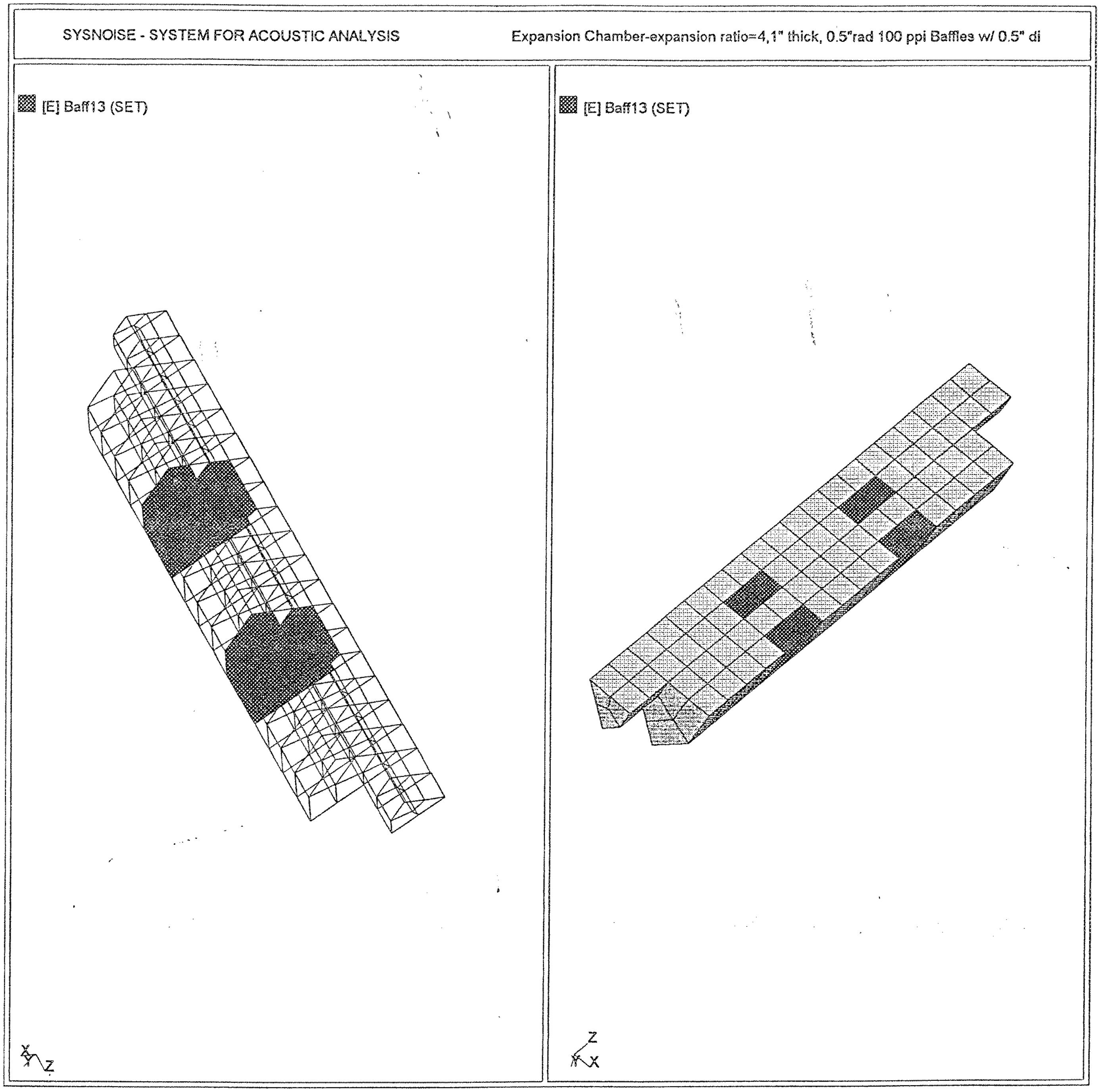


Figure 49.
SYSNOISE model (quarter-section) of 4" OD × 10" long expansion chamber with 1" diameter, 1" thick, 100-ppi SiC foam donut baffles with 0.5" diameter holes

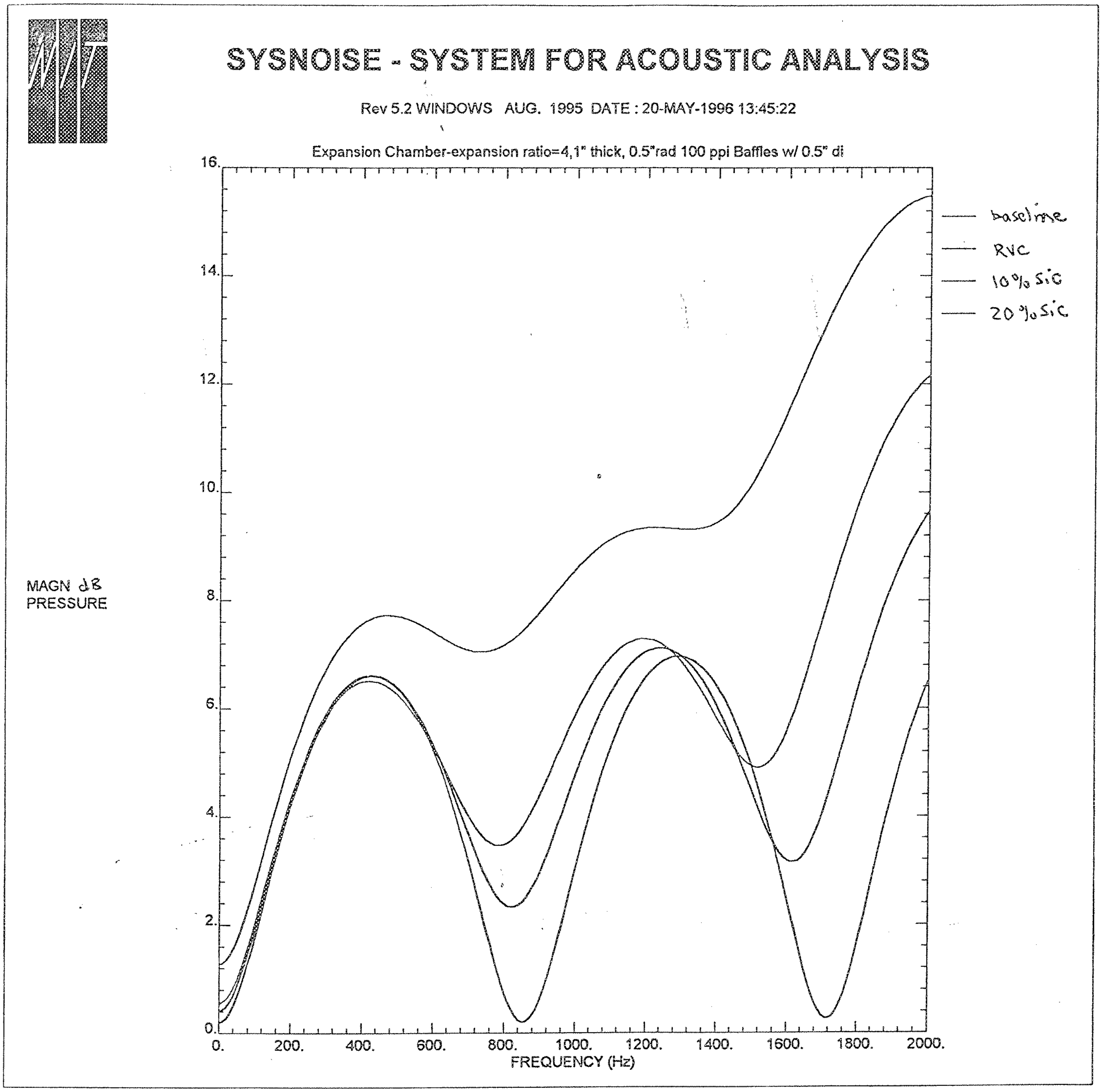


Figure 50.
Transmission loss vs. frequency for expansion chambers with 1" diameter, 1" thick, 100-ppi RVC and SiC foam donut baffles of various densities with 0.5" diameter holes

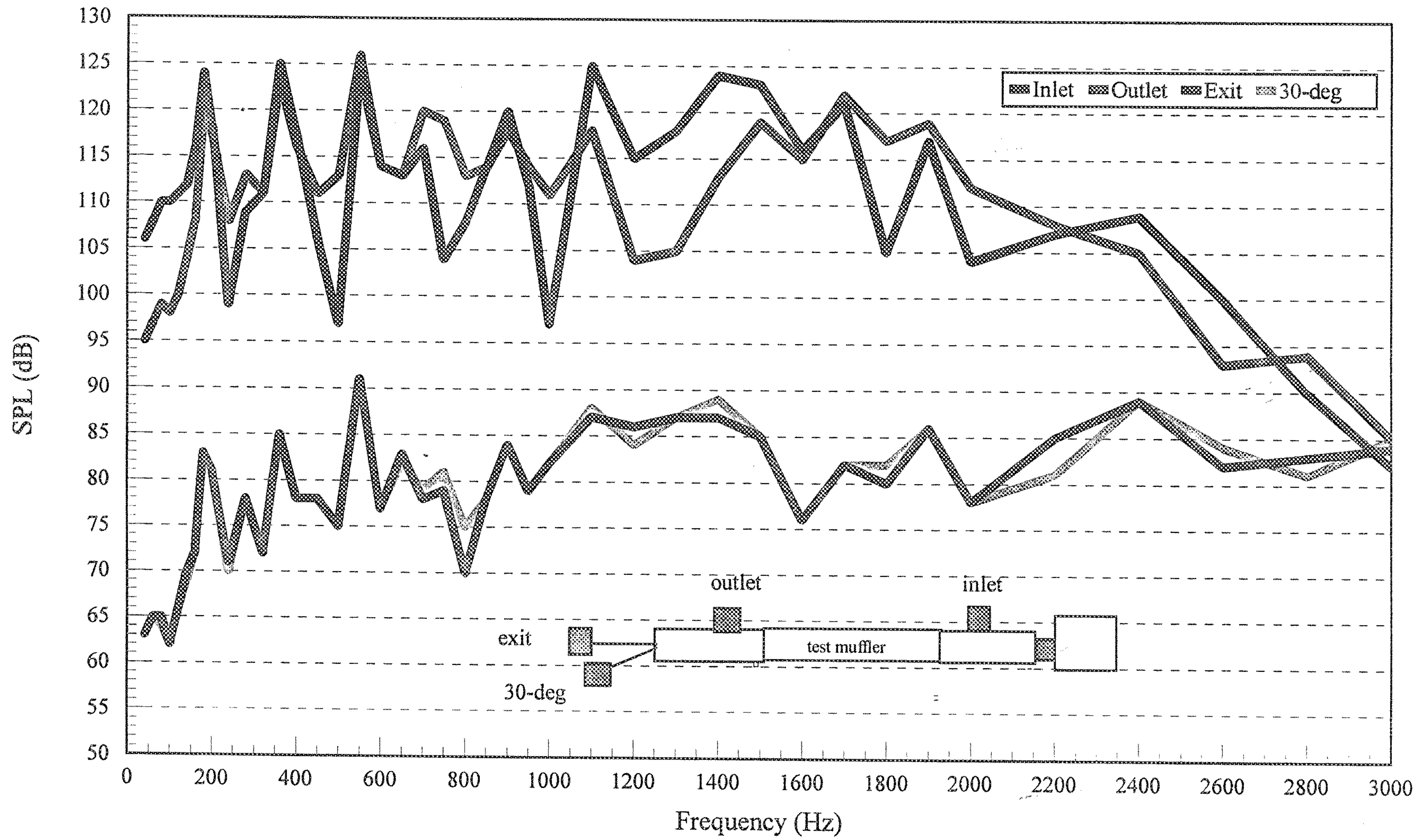


Figure 51.
Sound pressure level vs. frequency for baseline 2" ID × 11.5" long straight-pipe muffler measured using insertion loss measurement apparatus

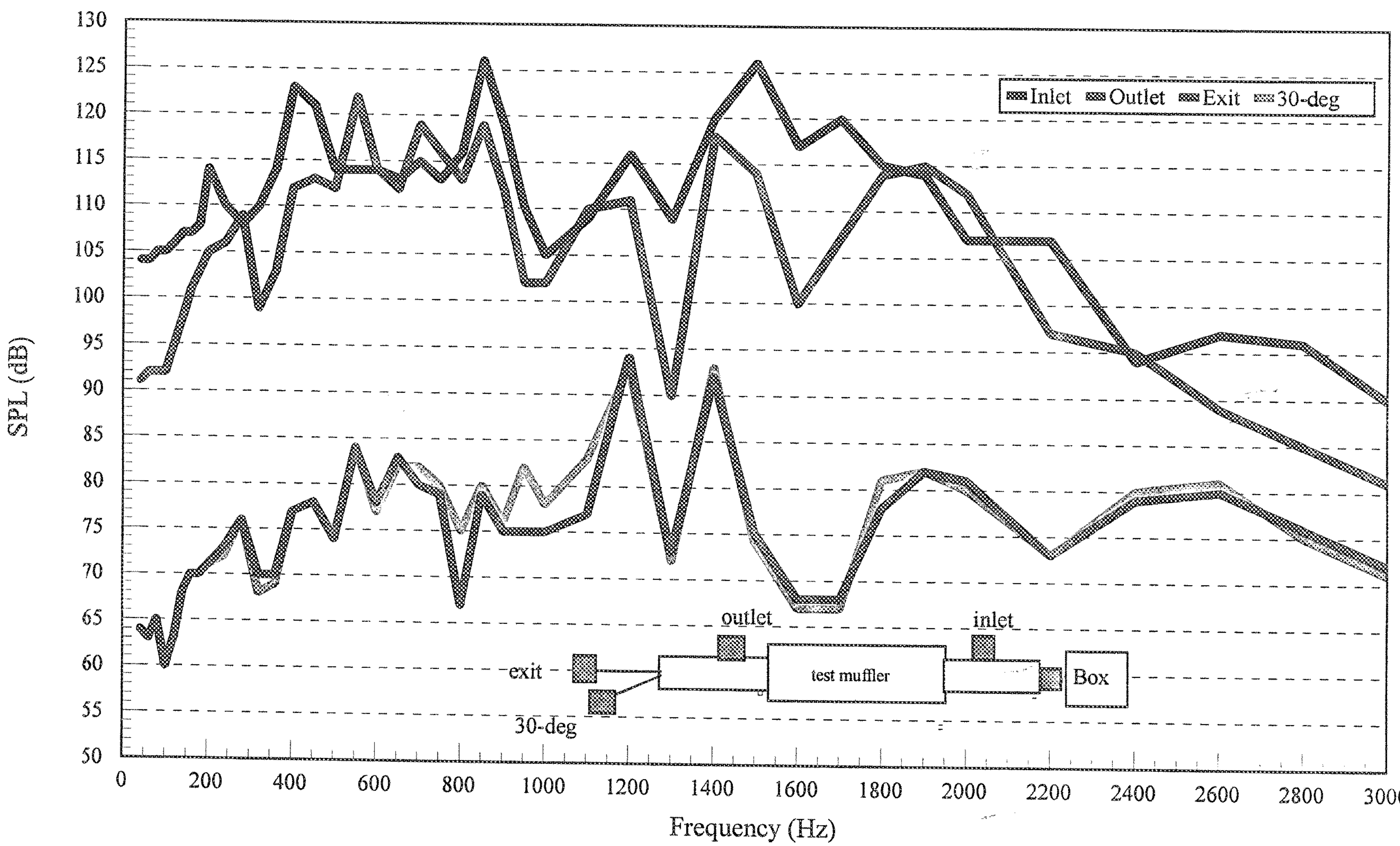


Figure 52.
Sound pressure level vs. frequency for baseline 4" ID × 11.5" long hollow expansion chamber muffler measured using insertion loss measurement apparatus

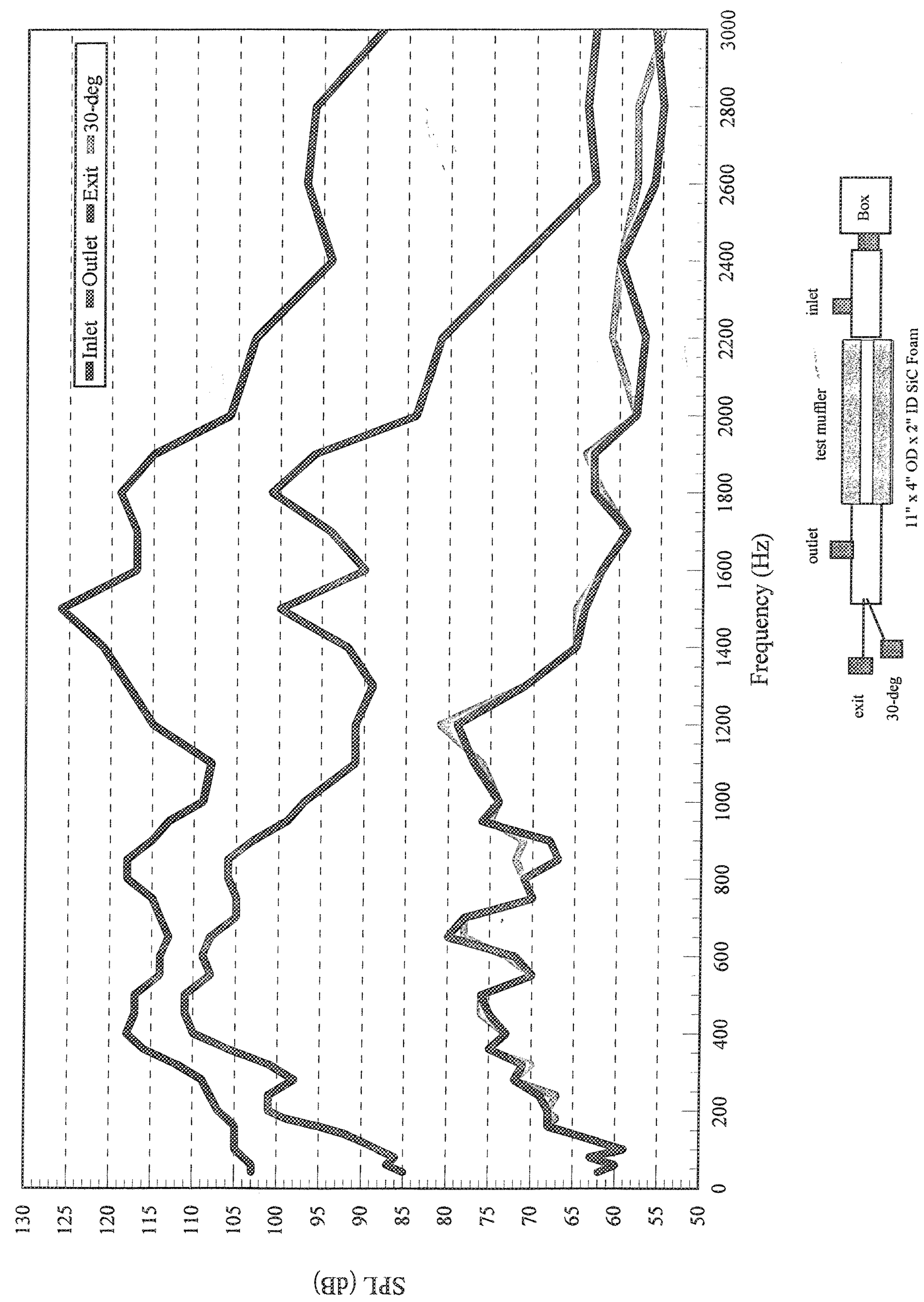


Figure 53.
Sound pressure level vs. frequency measured for prototype muffler #1 using insertion loss measurement apparatus

Figure 54.
Sound pressure level vs. frequency for prototype muffler #3 measured using insertion loss measurement apparatus

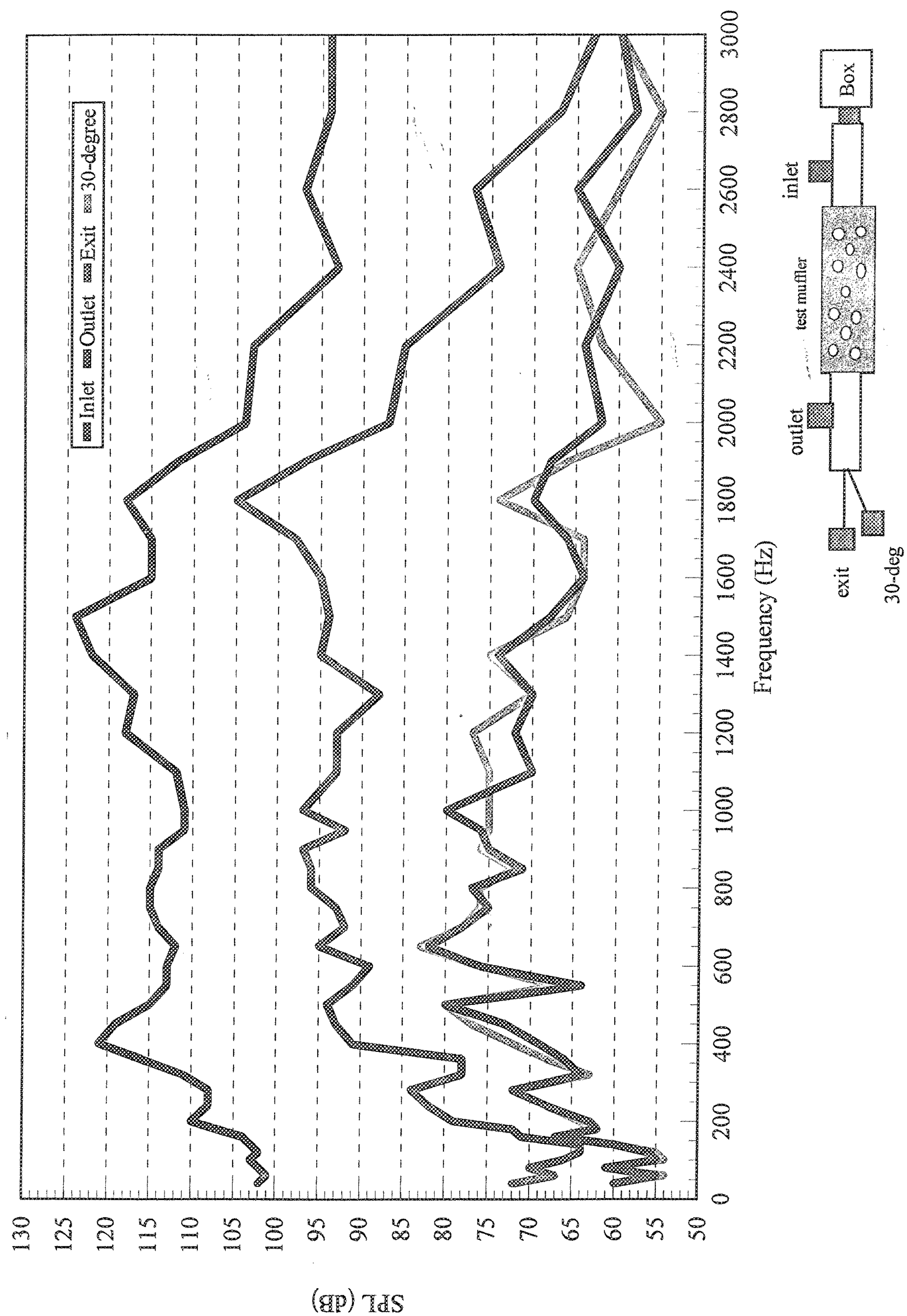


Figure 55.
Sound pressure level vs. frequency for prototype muffler #9 measured using insertion loss measurement apparatus

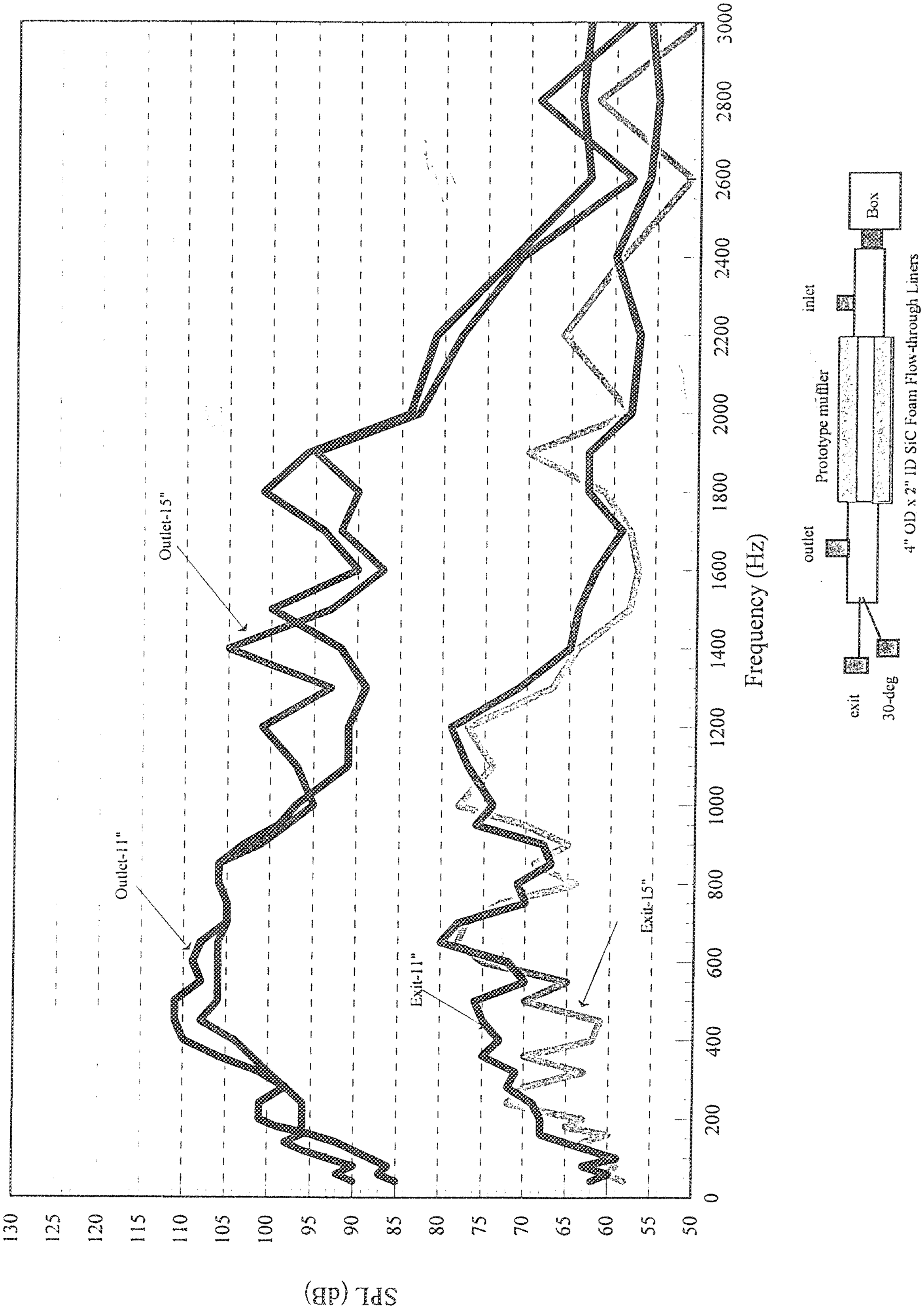


Figure 56.
Sound pressure level vs. frequency for 11" and 15" long prototype mufflers

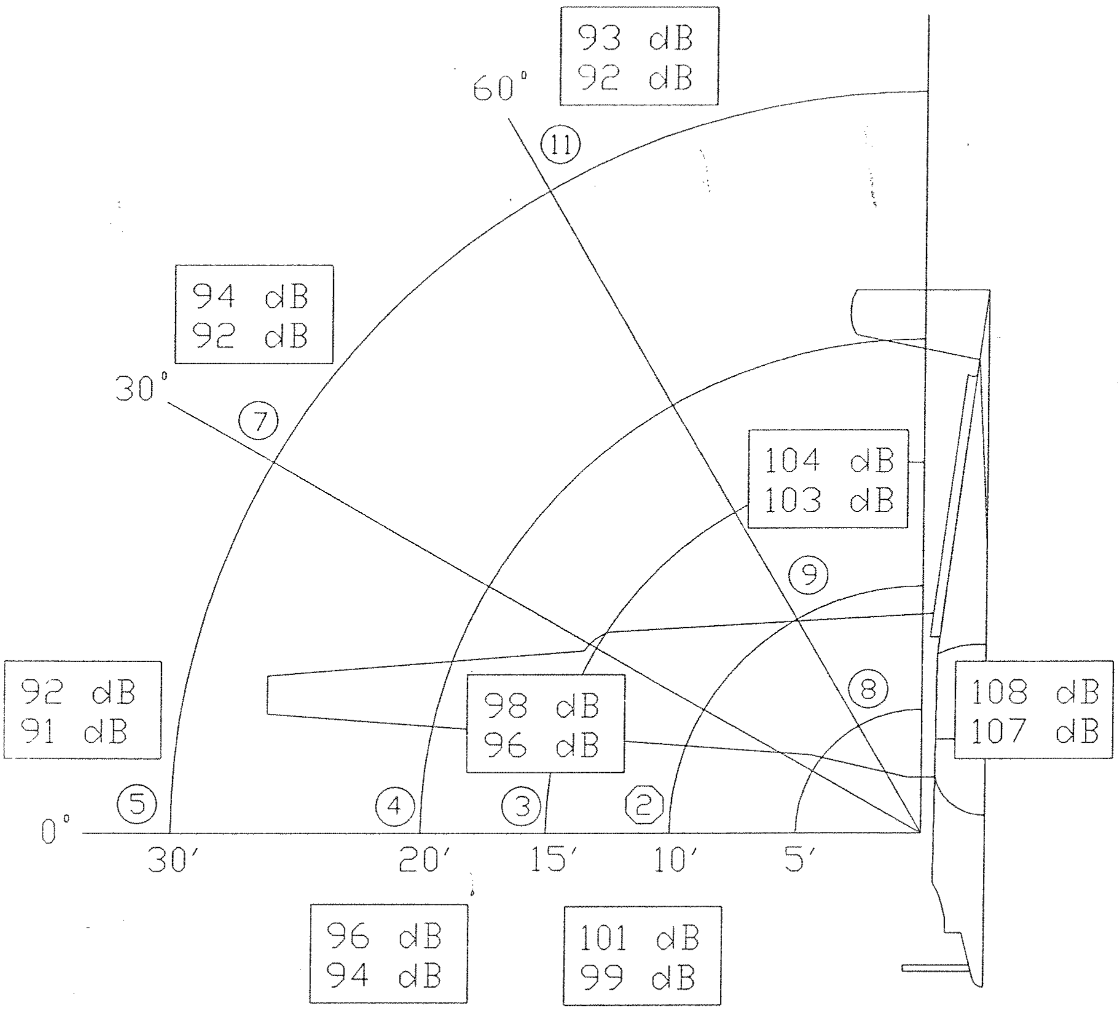


Figure 57.
Noise levels originating from short-pipe exhaust on YO-3A aircraft during ground testing (upper value: cowling off; lower value: cowling on)

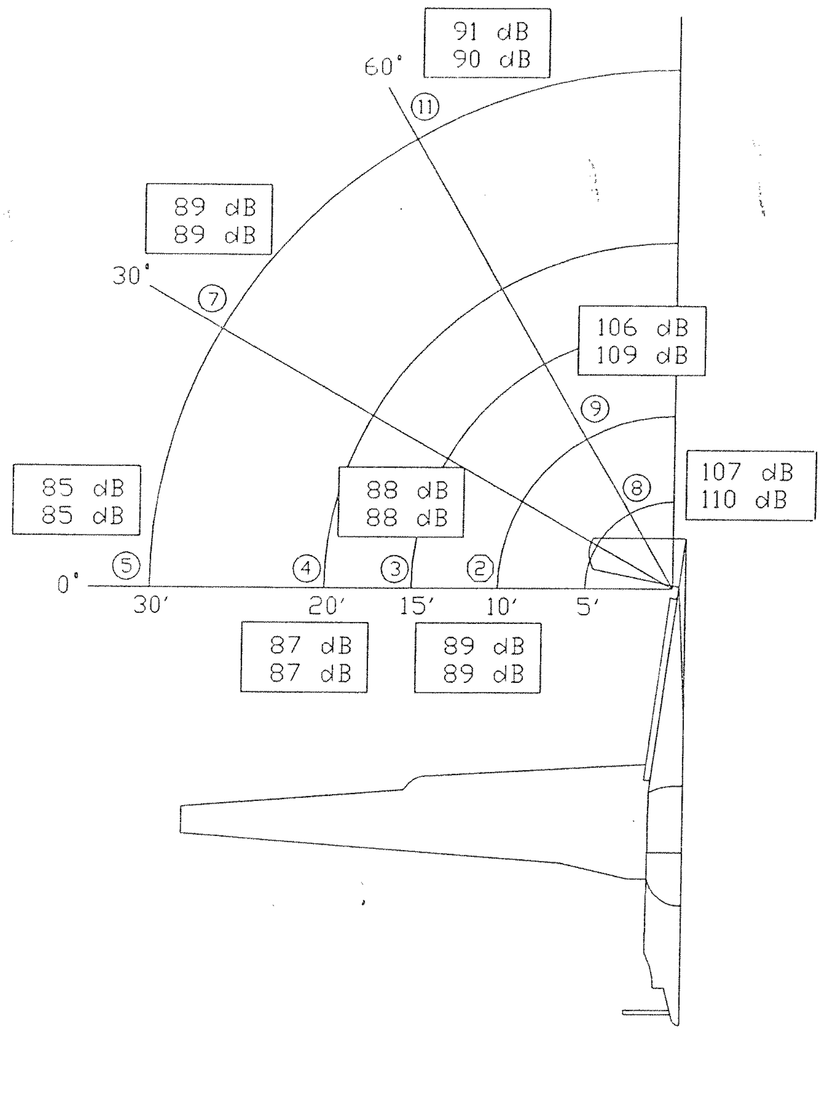


Figure 58.
Noise levels originating from long-pipe exhaust on YO-3A aircraft during ground testing (upper value: cowling off; lower value: cowling on)

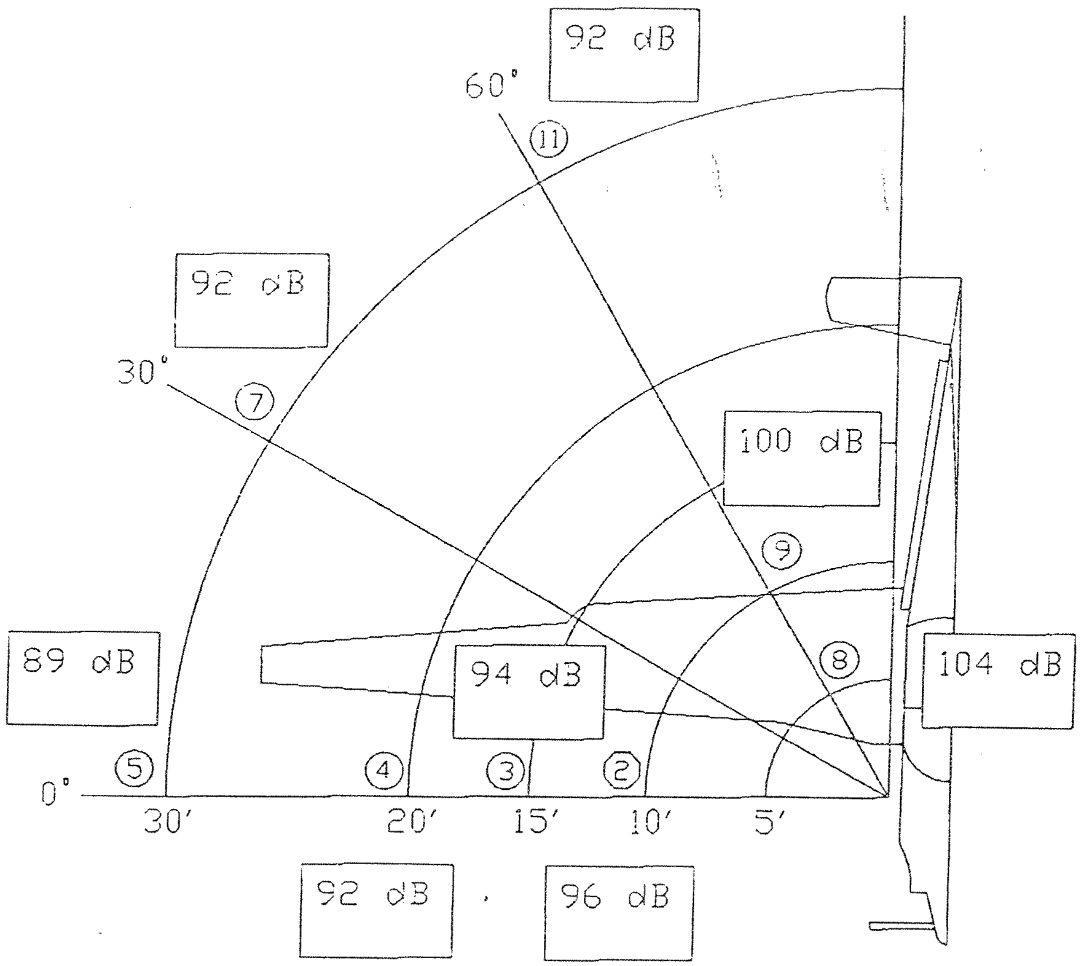
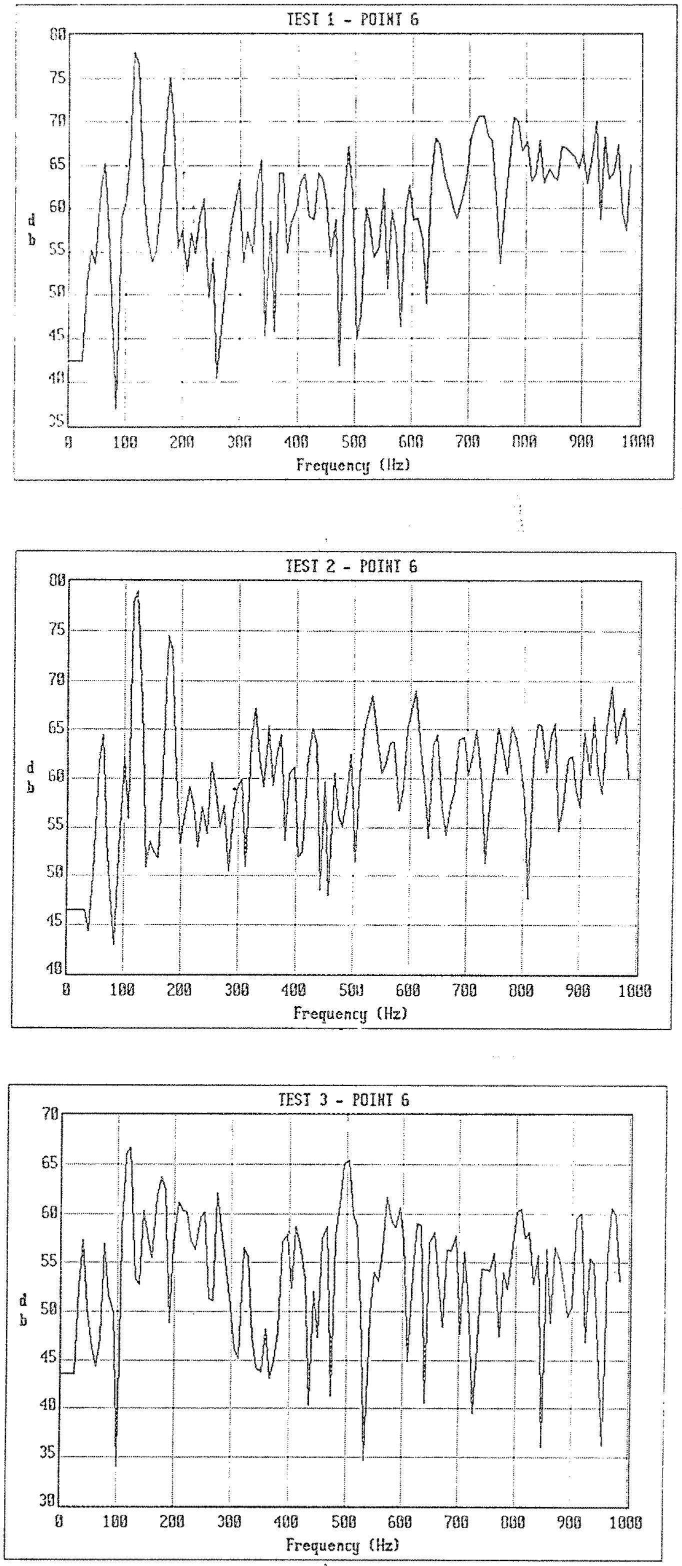
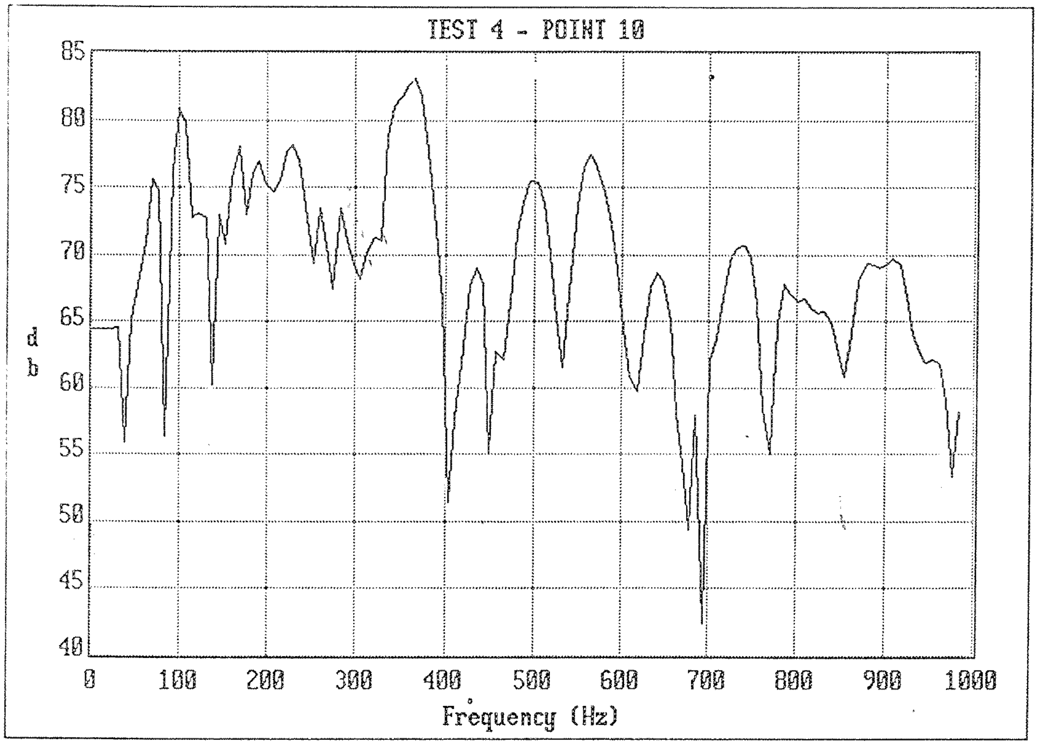
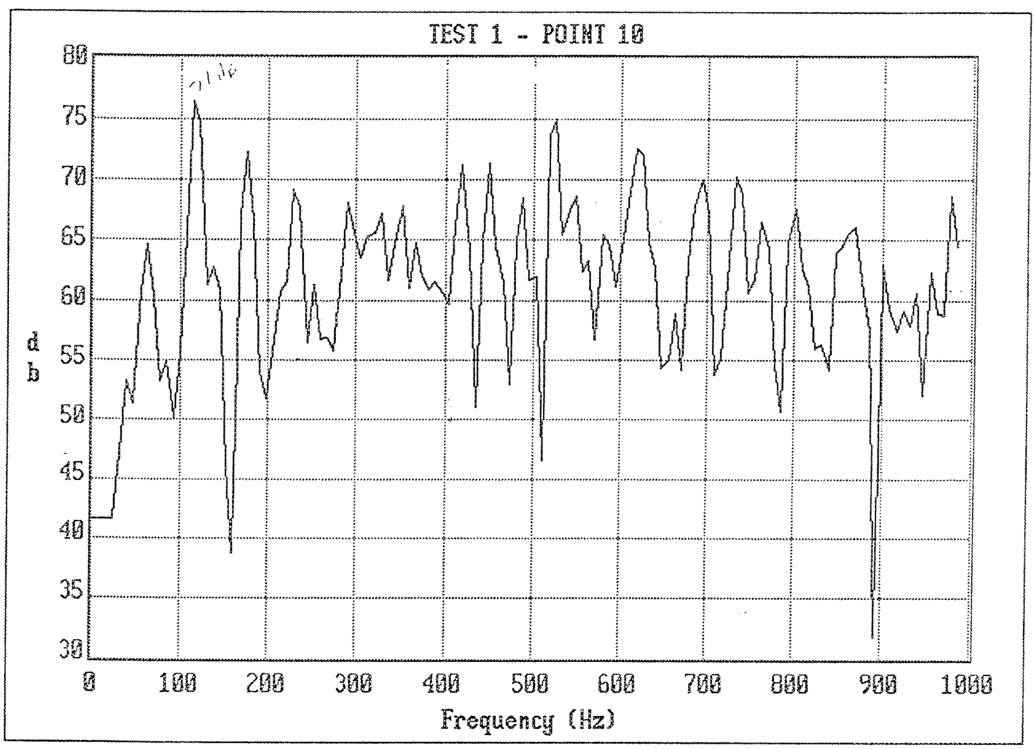


Figure 59.
Noise levels originating from long-pipe exhaust on YO-3A aircraft during ground testing with cowling off, with aircraft repositioned for comparison to short-pipe configuration

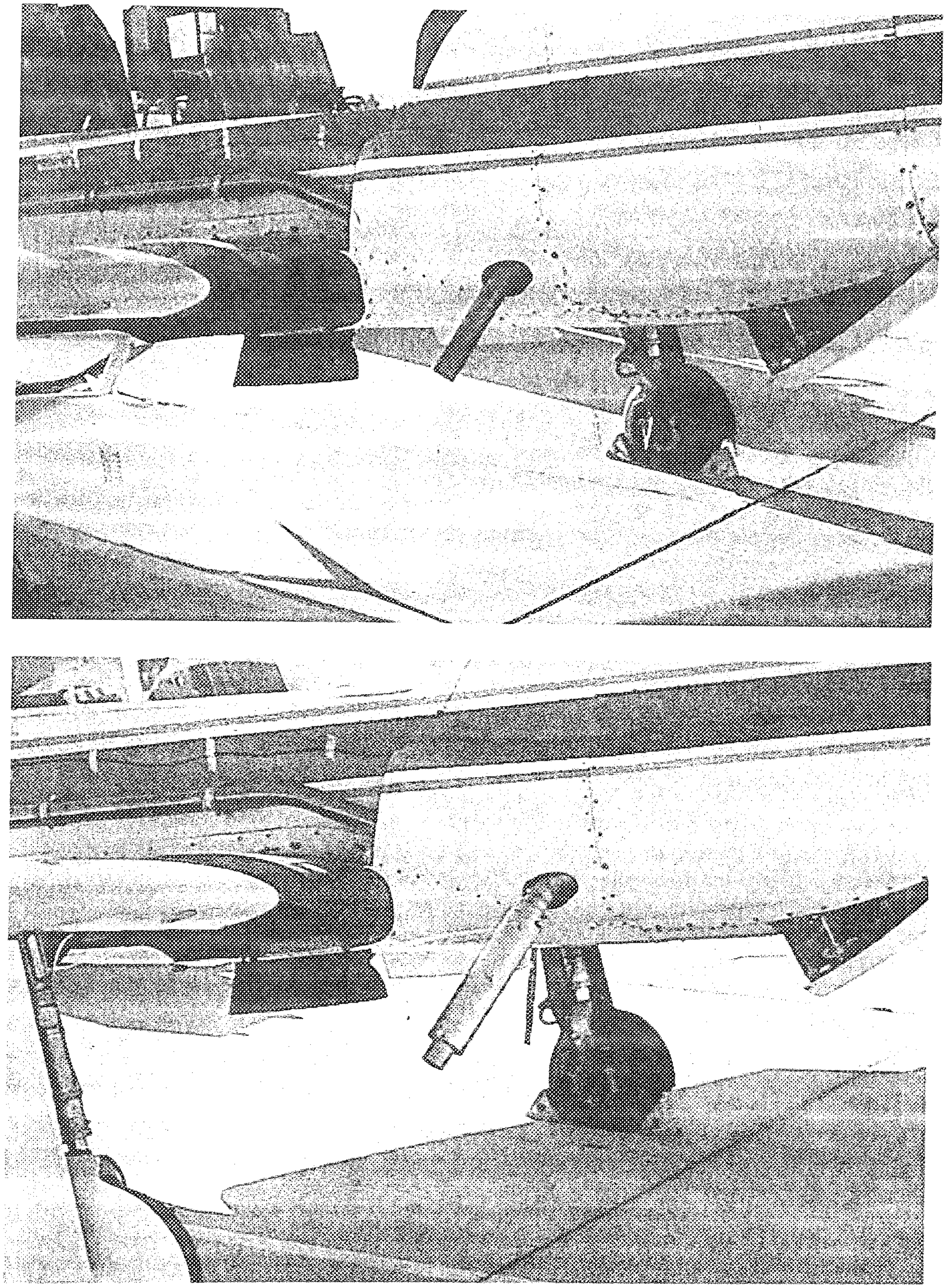


Figures 60A-C.
Sound pressure level vs. frequency at location #6 during ground testing of baseline short-pipe exhaust on YO-3A aircraft





Figures 61A-B.
Sound pressure level vs. frequency at location #10 during ground testing of baseline long-pipe exhaust on YO-3A aircraft



Figures 62A-B.
YO-3A aircraft with baseline stock short-pipe (top) and
SiC foam-based prototype (bottom) muffler test configurations

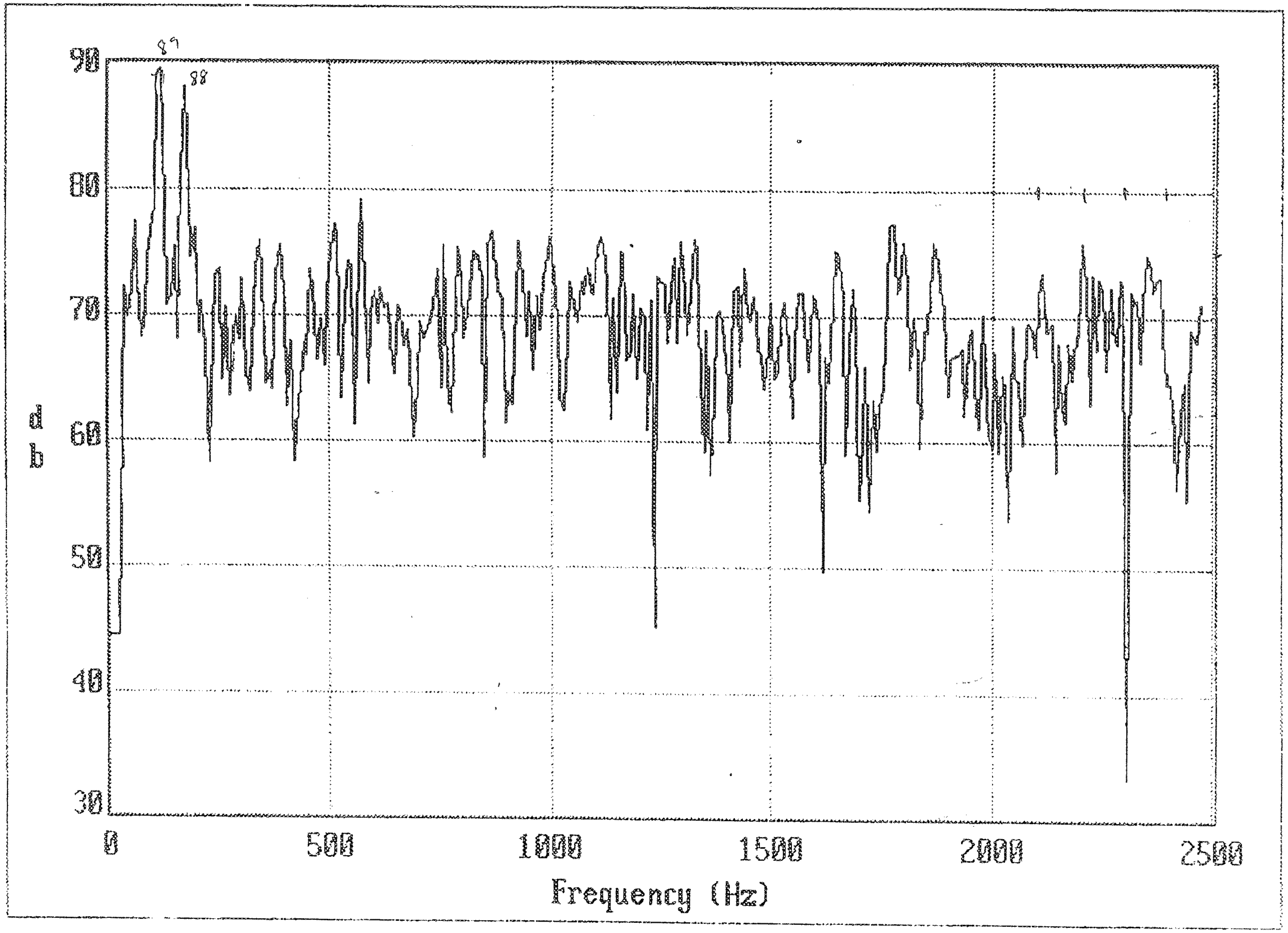


Figure 63.
Sound pressure level vs. frequency for prototype muffler #1 measured at location #1

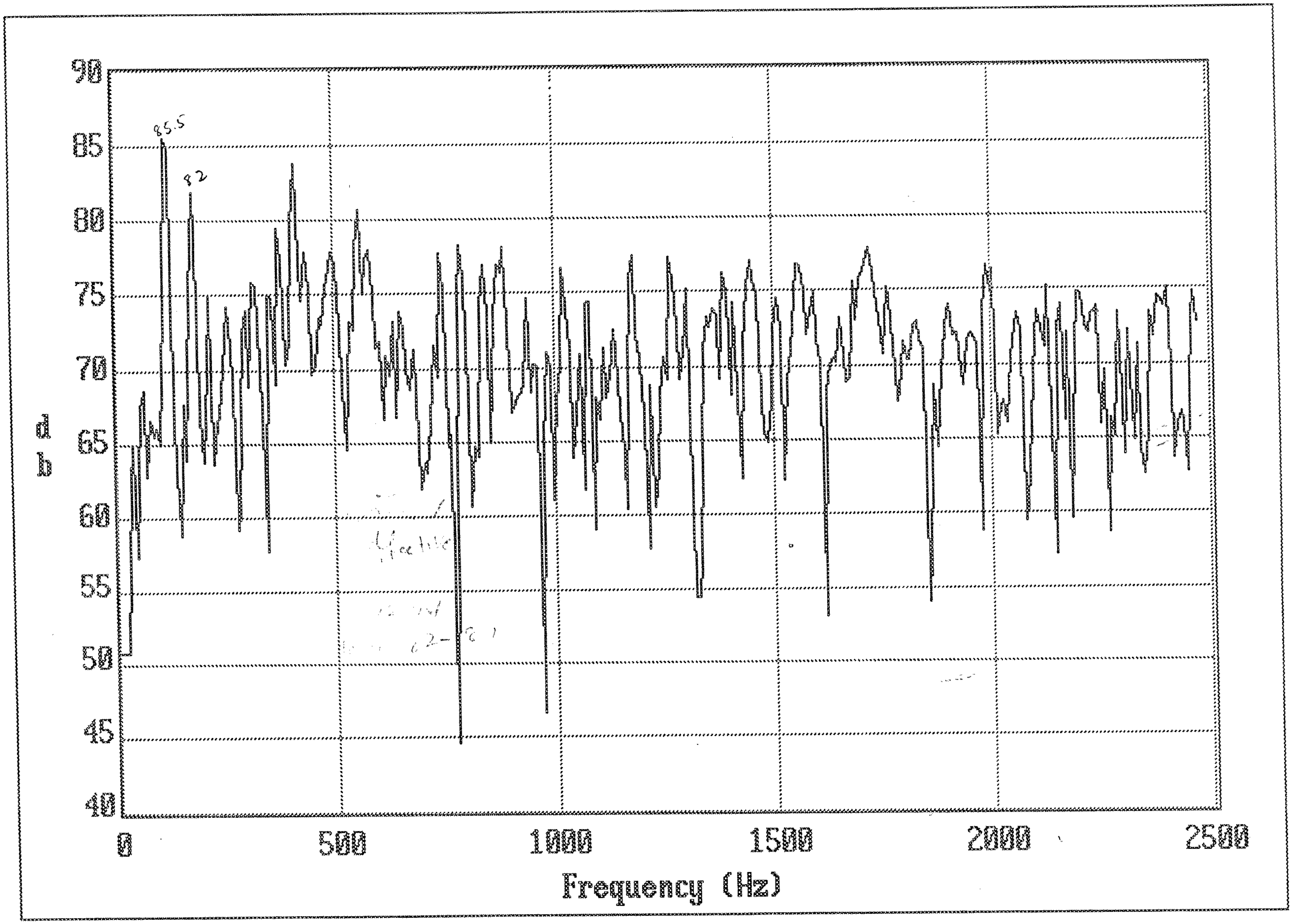


Figure 64.
Sound pressure level vs. frequency for prototype muffler #5 measured at location #1

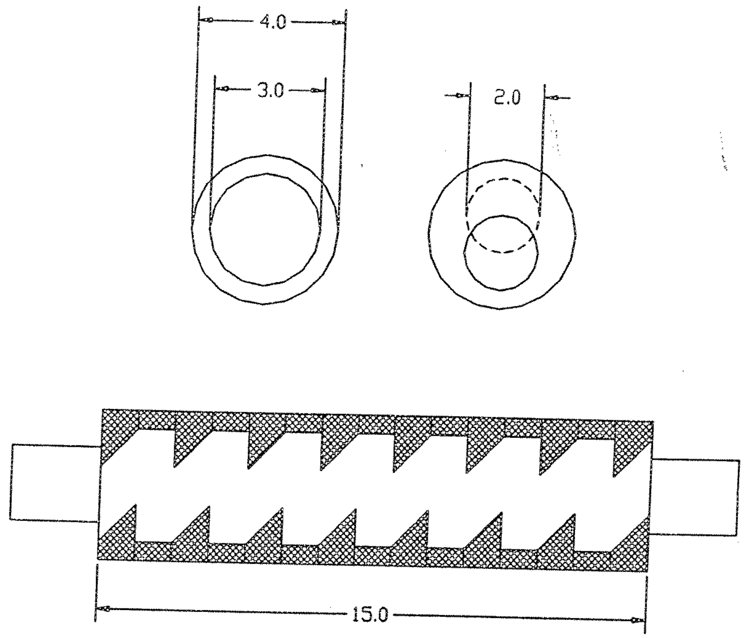


Figure 65.
Schematic of prototype muffler design #11, a 4" OD × 15" long straight pipe containing 4" OD × 3" ID RVC foam rings interspersed with 4" OD × 2" ID RVC foam rings with angled core holes

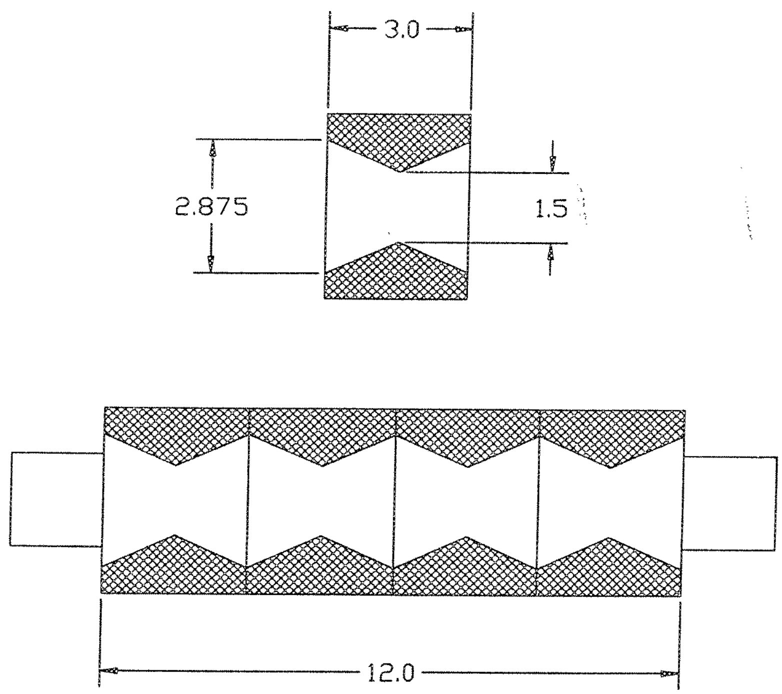


Figure 66.
Schematic of prototype muffler design #12, a 4" OD × 12" long straight pipe containing four 3" long RVC foam rings with "hourglass"-shaped core holes

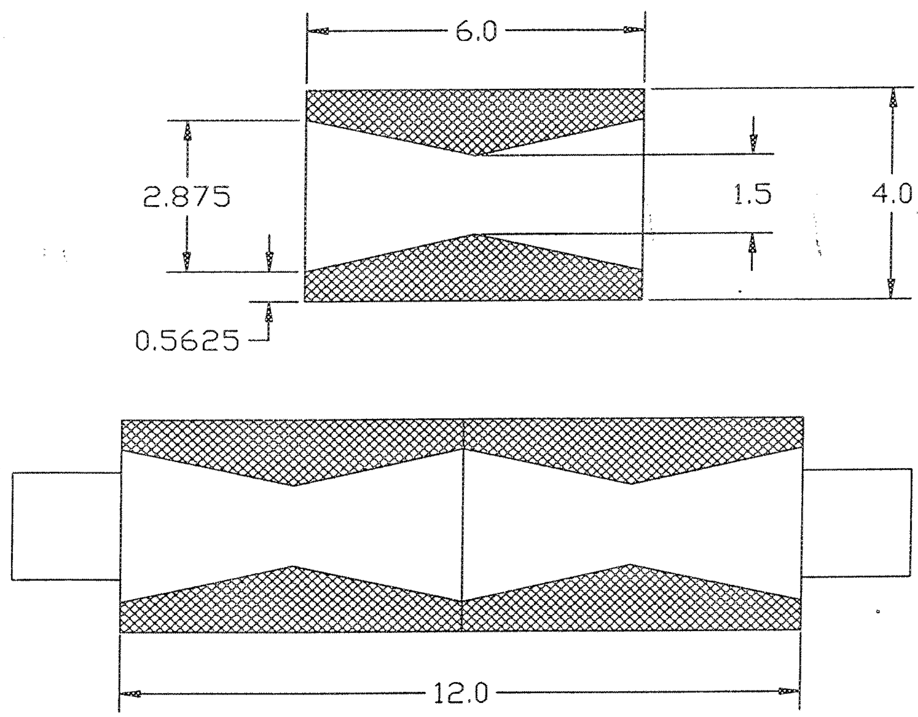


Figure 67.
Schematic of prototype muffler design #13, a 4" OD × 12" long straight pipe containing two 6" long RVC foam rings with "hourglass"-shaped core holes

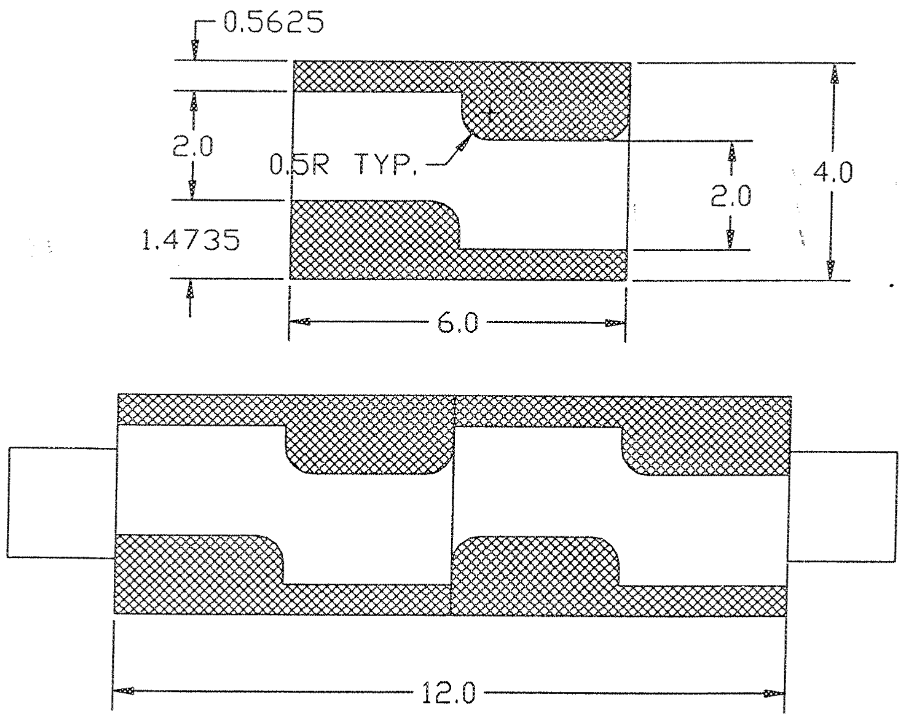


Figure 68.
Schematic of prototype muffler design #14, a 4" OD × 12" long straight pipe containing two 6" long RVC foam rings with 2" ID straight core holes with midpoint offsets

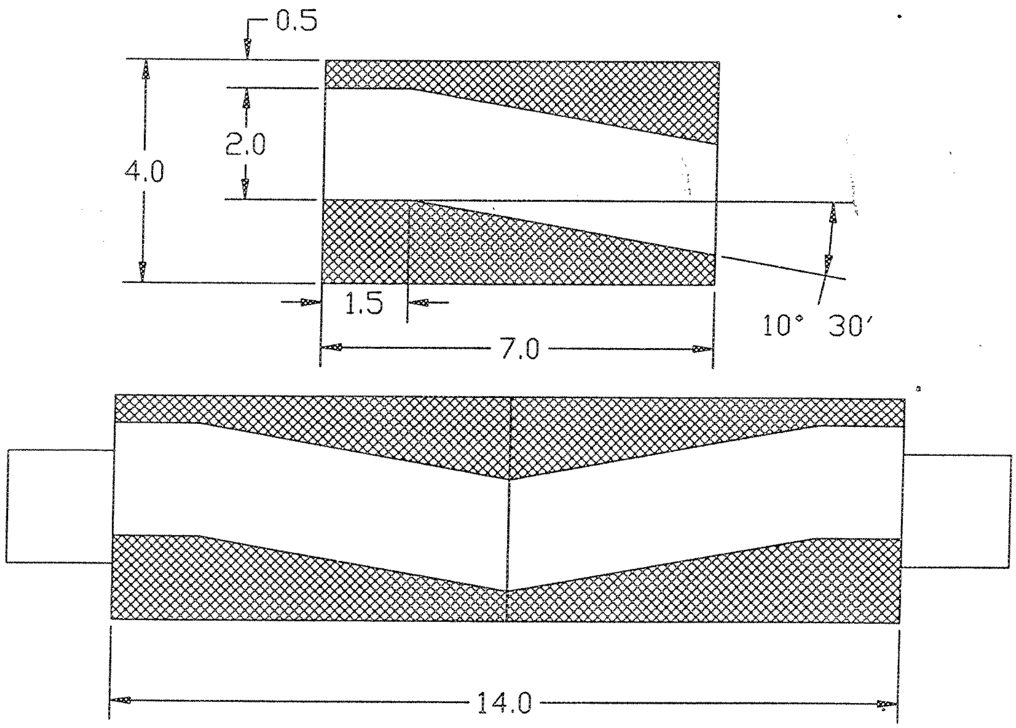


Figure 69.
Schematic of prototype muffler design #15, a 4" OD × 14" long straight pipe containing two 7" long RVC foam rings with 2" ID single-angled core holes

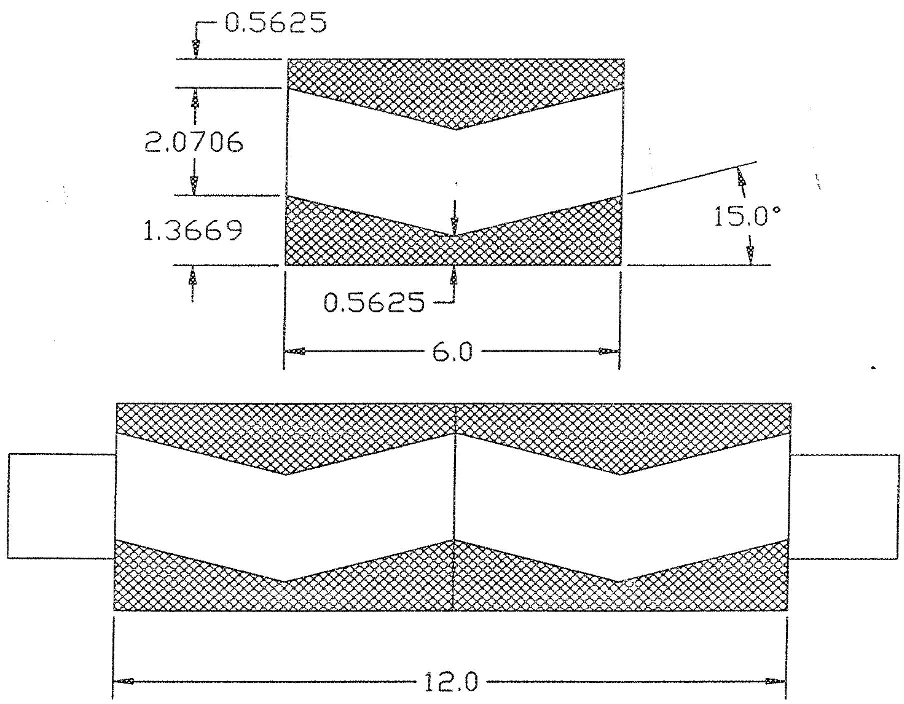


Figure 70.
Schematic of prototype muffler design #16, a 4" OD × 12" long straight pipe containing two 6" long RVC foam rings with 2" ID double-angled core holes

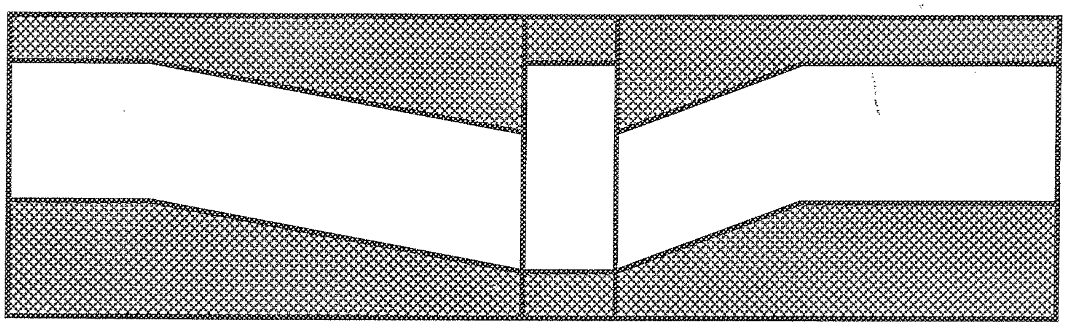


Figure 71.
Schematic of prototype muffler design #17, a straight pipe containing a long RVC foam ring with a single-angled core hole, a narrow RVC foam ring with a straight core hole, a short RVC foam ring with a single-angled core hole, and a short RVC foam ring with an straight, offset core hole

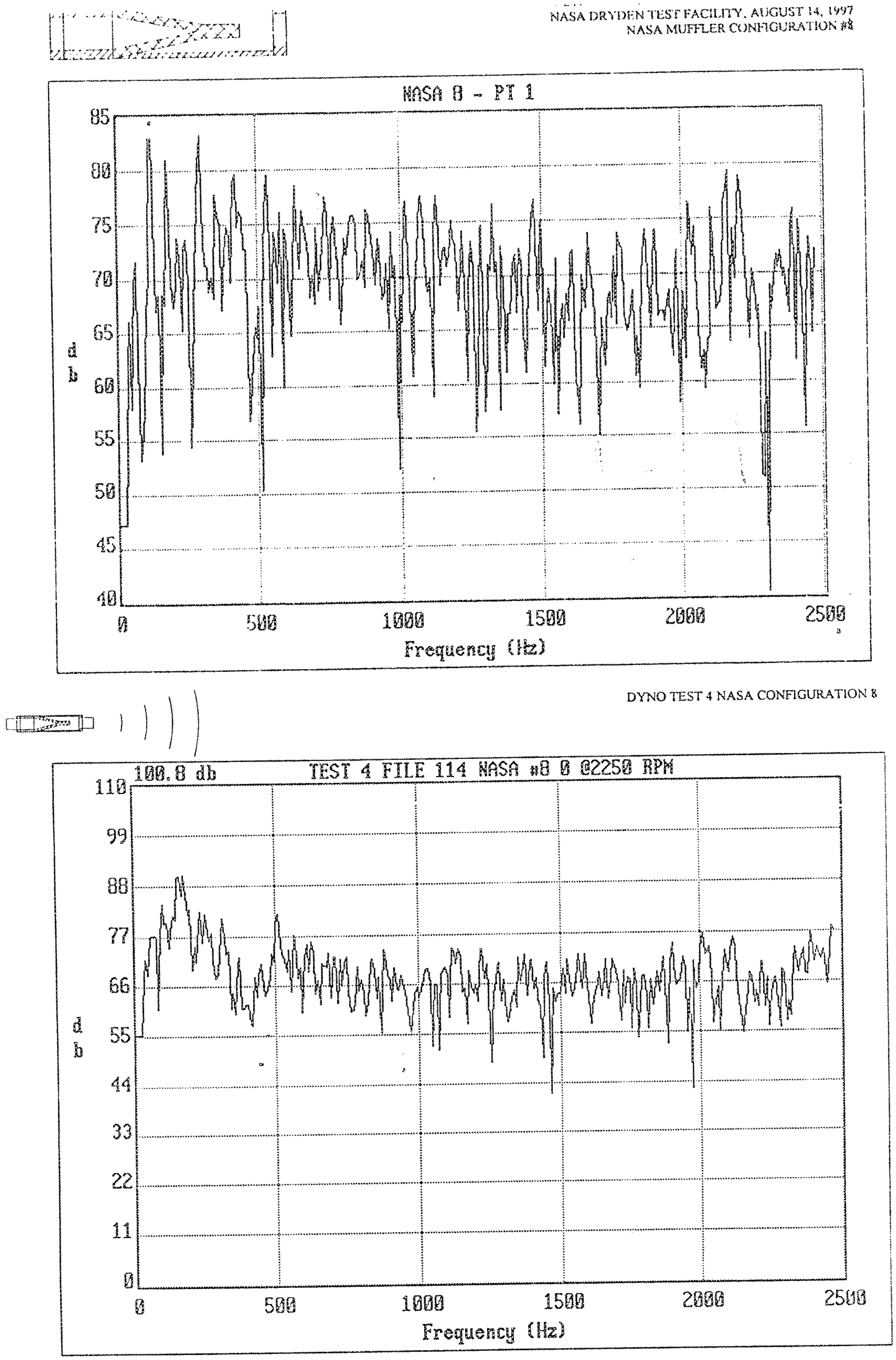


Figure 72A-B.
Sound pressure level vs. frequency for prototype muffler #8 measured at location #1 during ground (top) and dynamometer (bottom) testing

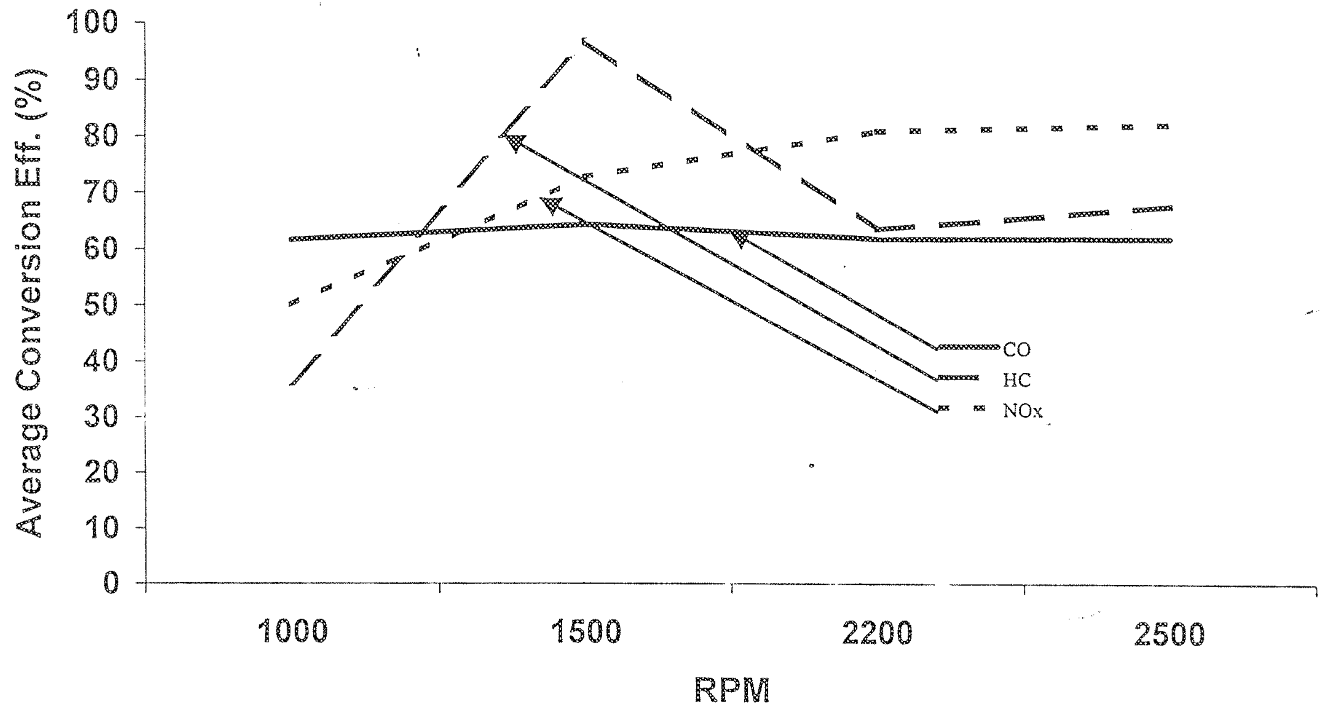


Figure 73.
Conversion efficiency vs. engine speed for Continental O-200 engine equipped with SiC foam-based catalytic converter

Table I.
Summary of Baseline Interior Noise Measurements
at Various Stages of Flight for Cessna 150 Aircraft

Flight condition	Engine speed (rpm)	Noise level (dB_A)
Ground run-up (static)	1702-1761	84.1-85.5
Takeoff/climb to 1000 ft	2518-2524	92.9-93.9
Cruise flight	2450	90.5-91.3
Cruise flight	2350	87.3-89.5
Cruise flight	2250	85.6-86.6
Cruise flight	2150	89.5-89.6
Cruise flight	2050	93.4
Maximum power	2683	90.8
Descent	1146 (power off)	85.3

Table II.
Summary of Fraction of Total Sound Energy Measured in Various Frequency Ranges for Continental O-200 Engine

	Frequency range (Hz)								
	<15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	>120
Percent of total energy	3.10	69.90	6.20	3.83	6.60	7.20	0.65	2.03	0.77

Table III.
Comparison of Commercial Muffler Sound Pressure Levels
with Baseline Cessna 150 Muffler

Commercial muffler type	Average difference vs. baseline (dB_A)
Genie	+0.032
Tri-Flow	-0.927
Borla (short)	-0.898
Borla (elliptical)	-0.670
Borla (long)	+1.373

Table IV.
Comparison of Commercial Muffler Backpressures
with Baseline Cessna 150 Muffler

Muffler type	Static pressure (inHg)	Pressure (2250 rpm) (inHg)	Backpressure (inHg)
Baseline	29.6	30.7	1.1
Genie	29.6	30.7	1.1
Tri-Flow	29.4	30.3	0,9
Borla (short)	29.6	30.6	1.0
Borla (elliptical)	29.5	30.5	1.0
Borla (long)	29.6	30.7	1.1
SuperTrap (@ 1 inHg)	29.4	30.5	1.1
SuperTrap (@ 2 inHg)	29.6	31.6	2.0

Table V.
Properties of Open-Cell Foam Materials Used for SYSNOISE Acoustic Modeling

Foam	Pore size (ppi)	Bulk density (g/cm^3)	Density (%)	Porosity (%)	Measured flow resistivity @ 1 m/sec (rayl/m)	Predicted flow resistivity @ 340 m/sec[1] (rayl/m)	Structural factor[2]
RVC	100	0.045	3	97	110	1560	1.136
RVC	200	0.16	5	95	307	10,000	1.227
RVC	400	0.19	5	95	1200	22,300	1.227
SiC	100	0.32	10	90	123	2230	1.45
SiC	100	0.61	20	80	510	8500	1.91

[1]Mach 1; based on linear relationship of various flow rates
[2]equal to $1 + 4.55(1-Y)$, where Y is material porosity

Table VI.
Sound Pressure Levels at Various Measurement Locations, and Backpressures, for Baseline and Prototype Mufflers Mounted on YO-3A Aircraft

Muffler type	Sound pressure level (dB_A) at measurement location #*n*								Backpressure (inHg)
	#2	#3	#4	#5	#7	#8[1]	#9[1]	#11	
First test series (10/96 at ARC)									
Baseline short pipe	99	96	94	90.5	90	106	103	90	0.8
Baseline long pipe	96	94	92	89	92	104	100	92	1.2
Prototype #1	96	93	91	88	89	106	103	89	0.9
Prototype #2	96	92.5	90.5	88	89	104	102	90	0.9
Prototype #3	--	--	--	--	--	--	--	--	≥5.0
Prototype #4	96	93	91	87.5	88	105	102	90	1.4
Second test series (8/97 at DFRC)									
Baseline short pipe[2]	100	96	95	91	90	107	103	90	3.8
Prototype #5	95	92	91	87	86	104	101	86	1.95
Prototype #6	95	92	91	88	87	102	101	87	1.05
Prototype #7	103	102	101	98	98	102	100	100	1.1
Prototype #8	103	101	101	98	97	107	102	100	1.15
Prototype #9	104	102	101	99	98	107	101	99	3.8
Prototype #10	101	99	97	95	94	104	100	101	--
Baseline short pipe[3]	105	103	102	99	98	108	102	100	--

[1]measured 1 ft off ground; others measured 4 ft off ground
[2]measured at start of test series
[3]measured at end of test series

Table VII.
Backpressures of Baseline and Prototype Mufflers
Mounted on Cessna 150 and YO-3A Aircraft

Muffler type	Weight (lb)	Backpressure (inHg)	
		Cessna 150	YO-3A
Baseline	--	0.9	0.75
Prototype #5	4.8	0.7	1.05
Prototype #6	4.0	1.1	3.8
Prototype #7	4.3	1.3	3.8
Prototype #8	3.8	0.8	1.1
Prototype #9	4.8	0.7	1.15
Prototype #10	4.2	0.9	1.95

Table VIII.
Sound Pressure Levels of Various Muffler Prototypes
at Various Major Frequencies Measured at Location #1

Freq	Baseline	Prot#5		Prot#6		Prot#7		Prot#8		Prot#9		Prot#10	
Hz	dB_A	dB_A	Δ	dB_A	Δ	dB_A	Δ	dB_A	Δ	dB_A	Δ	dB_A	Δ
38	62.5	65	+2.5	65	+2.5	62	-0.5	66.5	+4	66	+3.5	66	-0.5
75	72	68	-4.0	63.5	-8.5	64.5	-8.5	72	0	73	+1	64	-8
120	83	85.5	+2.0	77.5	-5.5	78	-5	84.5	+1.5	85	-2	81	-2
145	66.5	67.5	+1.0	63.5	-3	62	-4.5	68.5	+2	65	-1.5	64	-2.5
185	76.5	82	+5.5	76.5	0	76.5	0	81	+4.5	80	+3.5	73	-3.5
230	74.5	75	+0.5	69.5	-4	71.5	-3	74	-0.5	76	+1.5	75	+0.5
300	80	74	-6.0	68	-12	67	-13	83	+3	71.5	-8.5	79.5	-0.5
365	76.5	75	-1.5	74	-2.5	72.5	-4	77.5	+1	68	-7.5	77	+0.5
415	81	84	+3.0	83	2	80	-1	79.5	-1.5	84	+3	81	0
495	78	78	0	82	4	73	-5	66	-12	60	-18	74	-4
530	80	73	-7.0	74	-6	68	-12	79.5	-0.5	78	-2	69	-1
560	78	80.5	+1.5	77	-1	75.5	-2.5	74	-4	74	-4	79.5	+1.5
635	87	73	-15.0	78	-9	65	-22	78	-9	78.5	-8.5	83	-4
670	85	74	-11.0	67	-18	71.5	-13.5	76	-9	71	-14	62	-23
690	82	71.5	-10.5	73	-9	73	-9	70.5	-11.5	73	-9	84	+2
730	82	71.5	-10.5	77	-5	73	-9	77.5	-4.5	74	-8	78.5	-3.5
810	80	65	-15.0	74	-6	72	-8	74.5	-5.5	66	-14	72	-8
1050	82.5	76.5	-6.0	76.5	-6	77	-5.5	77.5	-5	75.5	-6	70	-12.5
1500	82.5	74.5	-8.0	73	-9.5	76.5	-6	75	-6.5	77	-5.5	71	-11.5
2300	77.5	74	-3.5	75	-2.5	77	-0.5	72	-4.5	73	-2.5	73.5	-2

Table IX.
Backpressures and Average Sound Pressure Levels
for Baseline and Various Prototype and Commercial Mufflers

Muffler type	Backpressure (inHg)	Average sound pressure level @ 2200 rpm (dB^A)[1]	
		0° axis	30° axis
Baseline straight pipe	1.0	109.4	108.1
Turbo Tuff	0.9	97.0	97.1
Prototype #5	0.9	99.1	96.2
Prototype #6	1.2	97.2	96.4
Prototype #8	0.8	101.2	100.1
Prototype #9	1.2	95.4	96.1
Prototype #10	1.0	98.2	98.3
Prototype #11	0.9	97.2	98.5
Prototype #12	1.0	100.5	99.4
Prototype #13	1.0	98.7	99.7
Prototype #14	1.0	96.6	98.9
Prototype #15	0.9	97.2	97.5
Prototype #16	1.0	98.0	97.8
Prototype #17	0.7	95.7	97.2

[1]measured using handheld dB meters

Table X.
Emissions Data for Continental O-200 Aircraft Engine
Without Catalytic Converter

Emission type	Idle (1500 rpm, no load)	1000 rpm	1500 rpm	2000 rpm	2500 rpm
CO	3.4%	3.0%	5.0%	11.95%	12.0%
CO_2	2.0%	1.9%	3.6%	6.75%	6.8%
O_2	15.8%	16.0%	12.0%	1.05%	1.1%
HC	1250 ppm	102.5 ppm	183.5 ppm	236.5 ppm	250 ppm
NO_x	63 ppm	34 ppm	89.5 ppm	105 ppm	110 ppm

Table XI.
Emissions Data for Continental O-200 Aircraft Engine
Equipped with SiC Foam-Based Catalytic Converter

Emission type	Idle (1500 rpm, no load)	1000 rpm	1500 rpm	2000 rpm	2500 rpm
CO	0.69%	1.2%	1.8%	4.6%	5.0%
CO_2	3.0%	1.6%	3.1%	3.7%	3.5%
O_2	16.5%	18.0%	15.3%	12.4%	12.5%
HC	215 ppm	65.5 ppm	6.2 ppm	86.5 ppm	81.5 ppm
NO_x	20 ppm	17 ppm	24.5 ppm	20.3 ppm	20 ppm

Table XII.
Backpressure of SiC Foam-Based Mufflers at Various Engine Speeds

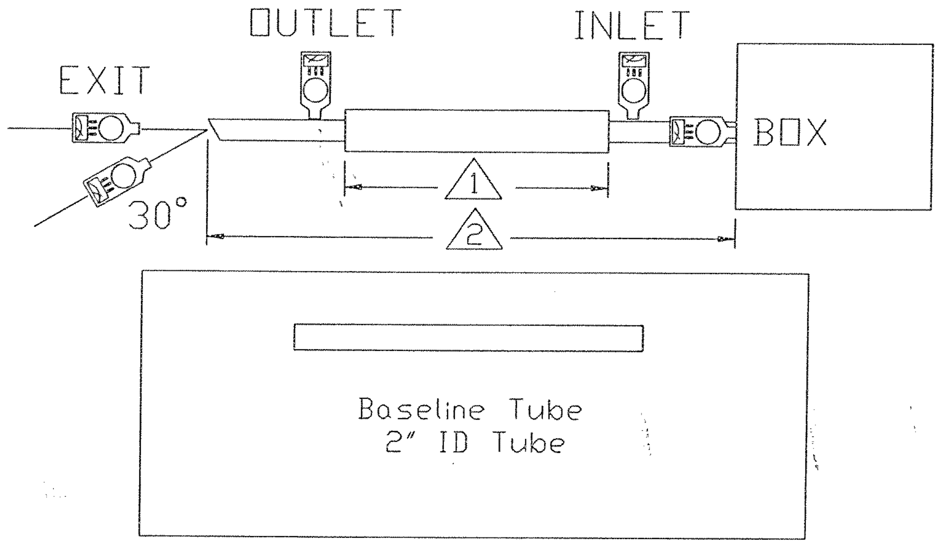
Cylinder	Pressure (inHg)						
	Static	1000 rpm	Backpressure	1500 rpm	Backpressure	2200 rpm	Backpressure
4	29.6	29.7	0.1	30.0	0.4	30.2	0.6
1	29.6	29.7	0.1	30.0	0.4	30.1	0.5

Table XIII.
Noise Levels Measured During Takeoff (Flight Profile #1)
for Cessna 150 Aircraft Equipped with SiC Foam-Based Mufflers

Event #	Altitude Observed	Max dB BBN 614 Ultrafoam	Max dB BBN 614 Cessna OEM	Max dB Handheld Ultrafoam	Max dB Handheld Cessna OEM
1	600		69.4		71
2	600		70.5		72
3	600		69.9		72
4	600		69.9		72
5	600		70.7		72
1	700	70.6		71	
2	700	69.3		72	
3	700	69.3		72	
14	NR	68.0		71	
Average		**69.3**	**70.1**	**71.5**	**71.8**

APPENDIX A.

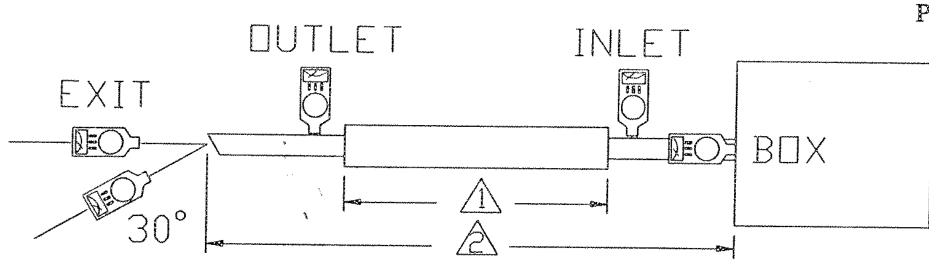
Sound Pressure Spectra Recorded from Prototype Mufflers
During Insertion Loss Measurement

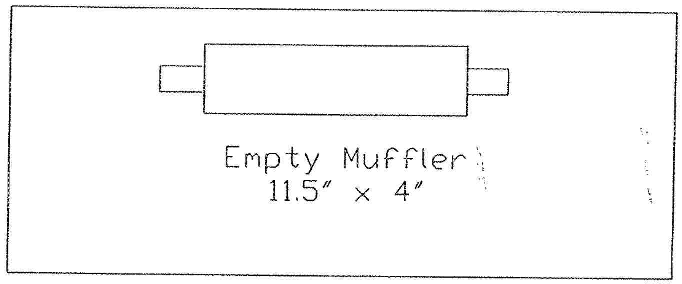


CONFIGURATION #1

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	106	95	63	63	11	47
60	16667	110	108	97	59:65	59:65	11	51
80	12500	110	110	99	65	64	11	45
100	10000	110	110	98	62	62	12	48
120	8333	110	111	100	60:66	60:66	11	50
140	7143	110	112	104	70	69	8	40
160	6250	110	116	108	72	72	8	38
180	5556	110	124	120	83	83	4	27
200	5000	110	118	117	81	81	1	29
240	4167	110	99	108	71	70	-9	39
280	3571	110	109	113	78	78	-4	32
320	3125	110	111	111	72	72	0	38
360	2778	110	125	123	85	85	2	25
400	2500	110	117	116	78	78	1	32
450	2222	110	106	111	78	78	-5	32
500	2000	110	97	113	75	75	-16	35
550	1818	110	124	>126	91	91	-2	19
600	1667	110	114	114	77	77	0	33

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	113	113	83	82	0	27
700	1429	110	116	120	78	79	-4	32
750	1333	110	104	119	79	81	-15	31
800	1250	110	108	113	70	75	-5	40
850	1176	110	114	114	78	78	0	32
900	1111	100	120	118	84	84	2	16
950	1053	110	112	114	79	79	-2	31
1000	1000	110	97	111	82	82	-14	28
1100	909	110	125	118	87	88	7	23
1200	833	110	115	104	86	84	11	24
1300	769	110	118	105	87	87	13	23
1400	714	110	124	113	87	89	11	23
1500	667	110	123	119	85	85	4	25
1600	625	110	116	115	76	76	1	34
1700	588	110	121	122	82	82	-1	28
1800	556	110	105	117	80	82	-12	30
1900	526	110	117	119	86	86	-2	24
2000	500	110	104	112	78	78	-8	32
2200	455	110	107	108	85	81	-1	25
2400	417	110	109	105	89	89	4	21
2600	385	110	100	93	82	84	7	28
2800	357	110	90	94	83	81	-4	27
3000	333	110	82	85	84	85	-3	26

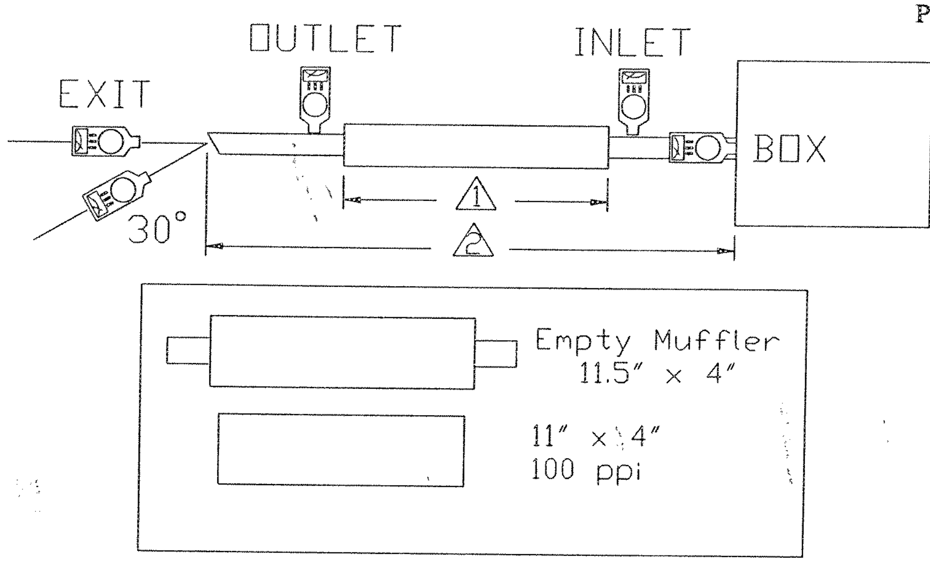




CONFIGURATION #2

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	104	91	64	64	13	46
60	16667	110	104	92	54:63	54:63	12	56
80	12500	110	105	92	65	65	13	45
100	10000	110	105	92	60	60	13	50
120	8333	110	106	95	63	63	11	47
140	7143	110	107	98	68	68	9	42
160	6250	110	107	101	70	70	6	40
180	5556	110	108	103	70	70	5	40
200	5000	110	114	105	71	71	9	39
240	4167	110	110	106	73	72	4	37
280	3571	110	108	109	76	76	-1	34
320	3125	110	110	99	70	68	11	40
360	2778	110	114	103	70	69	11	40
400	2500	110	123	112	77	77	11	33
450	2222	110	121	113	78	78	8	32
500	2000	110	114	112	74	74	2	36
550	1818	110	114	122	84	84	-8	26
600	1667	110	114	114	78	77	0	32

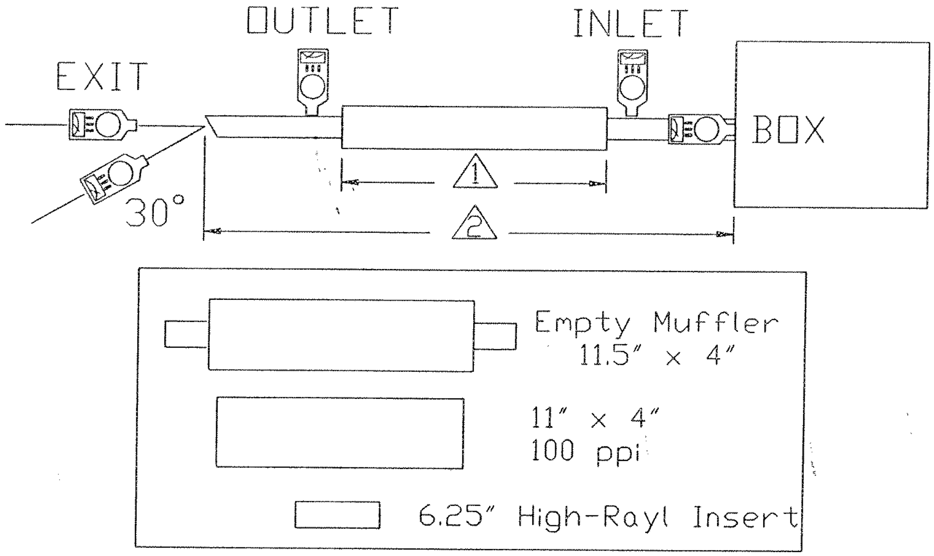
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	113	112	83	82	1	27
700	1429	110	115	119	80	82	-4	30
750	1333	110	113	116	79	80	-3	31
800	1250	110	116	113	67	75	3	43
850	1176	110	126	119	79	80	7	31
900	1111	110	119	112	75	76	7	35
950	1053	110	110	102	75	72	8	35
1000	1000	110	105	102	75	78	3	35
1100	909	110	109	110	77	83	-1	33
1200	833	110	116	111	94	93	5	16
1300	769	110	109	90	73	72	19	37
1400	714	110	120	118	92	93	2	18
1500	667	110	>126	114	75	74	12	35
1600	625	110	117	100	68	67	17	42
1700	588	110	120	107	68	67	13	42
1800	556	110	115	114	78	81	1	32
1900	526	110	114	115	82	82	-1	28
2000	500	110	107	112	81	80	-5	29
2200	455	110	107	97	73	73	10	37
2400	417	110	94	95	79	80	-1	31
2600	385	110	97	89	80	81	8	30
2800	357	110	96	85	76	75	11	34
3000	333	110	90	81	72	71	9	38



CONFIGURATION #3

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	103	85	62	62	18	48
60	16667	110	103	87	53:60	53:60	16	57
80	12500	110	104	86	63	63	18	47
100	10000	110	105	88	59	59	17	51
120	8333	110	105	90	50:62	50:62	15	60
140	7143	110	105	92	65	65	13	45
160	6250	110	105	95	68	68	10	42
180	5556	110	106	99	68	67	7	42
200	5000	110	107	101	68	68	6	42
240	4167	110	108	101	69	67	7	41
280	3571	110	109	98	72	72	11	38
320	3125	110	112	101	71	70	11	39
360	2778	110	116	106	75	75	10	35
400	2500	110	118	110	73	73	8	37
450	2222	110	117	111	75	76	6	35
500	2000	110	117	111	76	76	6	34
550	1818	110	114	108	70	70	6	40
600	1667	110	114	109	72	73	5	38

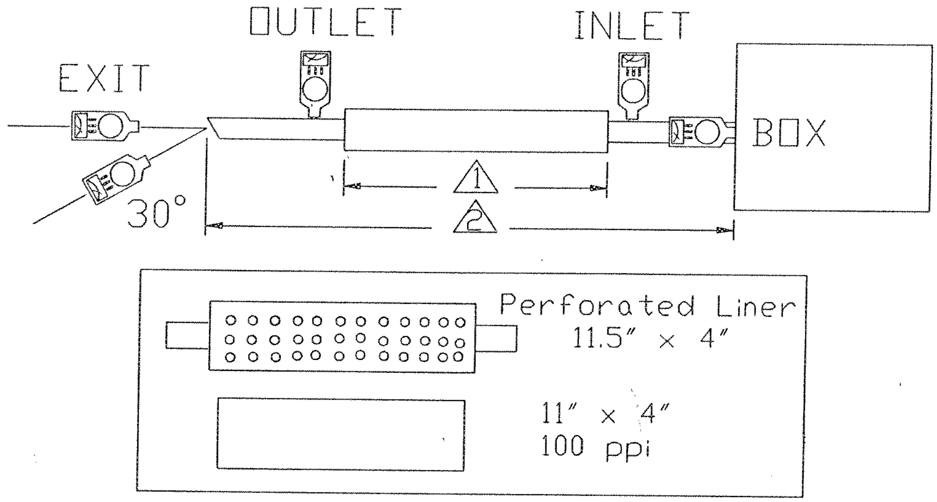
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	113	108	80	78	5	30
700	1429	110	114	105	78	78	9	32
750	1333	110	115	105	70	70	10	40
800	1250	110	118	106	71	71	12	39
850	1176	110	118	106	67	72	12	43
900	1111	110	115	103	68	71	12	42
950	1053	110	113	99	76	75	14	34
1000	1000	110	109	97	74	74	12	36
1100	909	110	108	91	77	76	17	33
1200	833	110	115	91	79	81	24	31
1300	769	110	118	89	71	71	29	39
1400	714	110	121	92	65	65	29	45
1500	667	110	>126	100	64	65	26	46
1600	625	110	117	90	62	62	27	48
1700	588	110	117	94	59	59	23	51
1800	556	110	119	101	63	62	18	47
1900	526	110	115	96	63	64	19	47
2000	500	110	106	84	58	58	22	52
2200	455	110	103	81	57	61	22	53
2400	417	110	94	72	60	60	22	50
2600	385	110	97	63	56	58	34	54
2800	357	110	96	64	55	58	32	55
3000	333	110	88	63	56	55	25	54



CONFIGURATION #4

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	105	86	61	61	19	49
60	16667	110	105	87	59	59	18	51
80	12500	110	105	87	62	63	18	48
100	10000	110	105	88	56	56	17	54
120	8333	110	106	90	55-59	55-59	16	55
140	7143	110	106	93	65	65	13	45
160	6250	110	106	95	69	69	11	41
180	5556	110	107	97	67	68	10	43
200	5000	110	108	100	64	64	8	46
240	4167	110	107	100	64	64	7	46
280	3571	110	109	98	72	72	11	38
320	3125	110	112	100	68	67	12	42
360	2778	110	115	104	75	76	11	35
400	2500	110	116	107	60	64	9	50
450	2222	110	115	108	72	74	7	38
500	2000	110	115	109	75	76	6	35
550	1818	110	112	107	64	64	5	46
600	1667	110	112	106	77	77	6	33

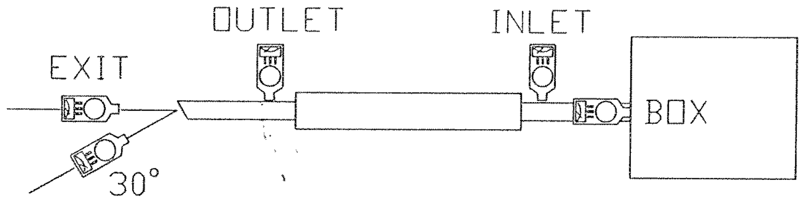
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	106	79	79	5	31
700	1429	110	112	104	77	76	8	33
750	1333	110	114	104	76	76	10	34
800	1250	110	117	106	68	70	11	42
850	1176	110	116	104	68	72	12	42
900	1111	110	112	99	69	71	13	41
950	1053	110	110	96	77	78	14	33
1000	1000	110	108	95	80	77	13	30
1100	909	110	108	95	70	65	13	40
1200	833	110	116	98	76	82	18	34
1300	769	110	116	86	71	73	30	39
1400	714	110	122	90	60	68	32	50
1500	667	110	125	92	66	65	33	44
1600	625	110	116	92	65	64	24	45
1700	588	110	117	94	59	63	23	51
1800	556	110	117	99	62	65	18	48
1900	526	110	109	93	58	61	16	52
2000	500	110	104	83	56	56	21	54
2200	455	110	98	78	55	55	20	55
2400	417	110	94	69	56	55	25	54
2600	385	110	98	64	55	55	34	55
2800	357	110	96	63	55	55	33	55
3000	333	110	92	63	56	55	29	54

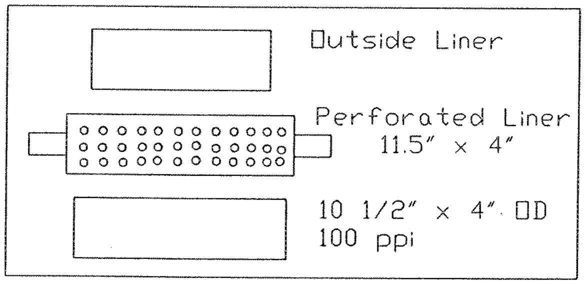


CONFIGURATION #5

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	102	72	60	60	30	50
60	16667	110	101	67	55	54	34	55
80	12500	110	102	70	61	61	32	49
100	10000	110	103	66	55	54	37	55
120	8333	110	102	64	56	55	38	54
140	7143	110	103	64	60	60	39	50
160	6250	110	104	71	67	66	33	43
180	5556	110	107	72	62	63	35	48
200	5000	110	110	79	63	64	31	47
240	4167	110	108	82	68	68	26	42
280	3571	110	108	84	72	72	24	38
320	3125	110	111	78	64	63	33	46
360	2778	110	116	78	66	68	38	44
400	2500	110	121	91	69	72	30	41
450	2222	110	119	93	73	77	26	37
500	2000	110	115	94	80	80	21	30
550	1818	110	113	91	64	67	22	46
600	1667	110	113	89	76	76	24	34

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	95	82	83	17	28
700	1429	110	114	92	78	78	22	32
750	1333	110	115	93	75	76	22	35
800	1250	110	115	96	77	76	19	33
850	1176	110	114	96	71	72	18	39
900	1111	110	114	97	75	76	17	35
950	1053	110	111	92	76	75	19	34
1000	1000	110	111	97	80	75	14	30
1100	909	110	112	93	70	75	19	40
1200	833	110	118	93	72	77	25	38
1300	769	110	117	88	70	70	29	40
1400	714	110	122	95	74	75	27	36
1500	667	110	124	94	68	66	30	42
1600	625	110	115	95	64	64	20	46
1700	588	110	115	98	66	64	17	44
1800	556	110	118	105	70	74	13	40
1900	526	110	112	97	68	66	15	42
2000	500	110	104	87	62	55	17	48
2200	455	110	103	85	64	62	18	46
2400	417	110	93	74	60	65	19	50
2600	385	110	97	77	65	60	20	45
2800	357	110	94	67	58	55	27	52
3000	333	110	94	63	60	60	31	50



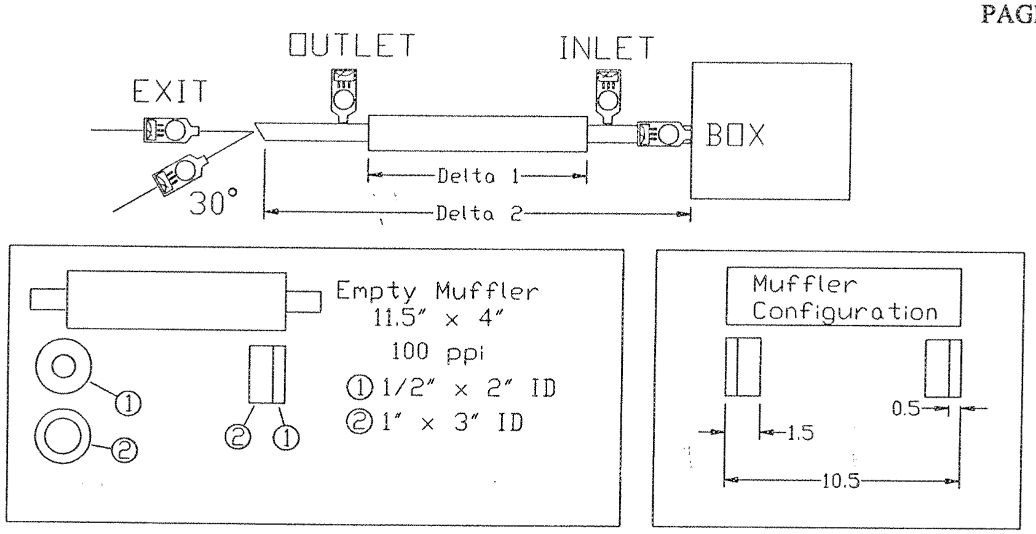


9 1/2" liner was secured around the perforated liner leaving two rows of holes exposed to the ambient air.

CONFIGURATION #6

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	103	78	58	58	25	52
60	16667	110	104	79	52	52	25	58
80	12500	110	104	80	61	61	24	49
100	10000	110	104	79	55	55	25	55
120	8333	110	104	80	55	54	24	55
140	7143	110	104	82	59	61	22	51
160	6250	110	105	85	68	67	20	42
180	5556	110	107	88	68	68	19	42
200	5000	110	110	97	64	65	13	46
240	4167	110	107	99	64	64	8	46
280	3571	110	107	96	74	75	11	36
320	3125	110	110	97	67	67	13	43
360	2778	110	114	101	74	76	13	36
400	2500	110	120	107	70	73	13	40
450	2222	110	117	108	75	76	9	35
500	2000	110	115	108	76	76	7	34
550	1818	110	113	106	62	60	7	48
600	1667	110	113	104	73	76	9	37

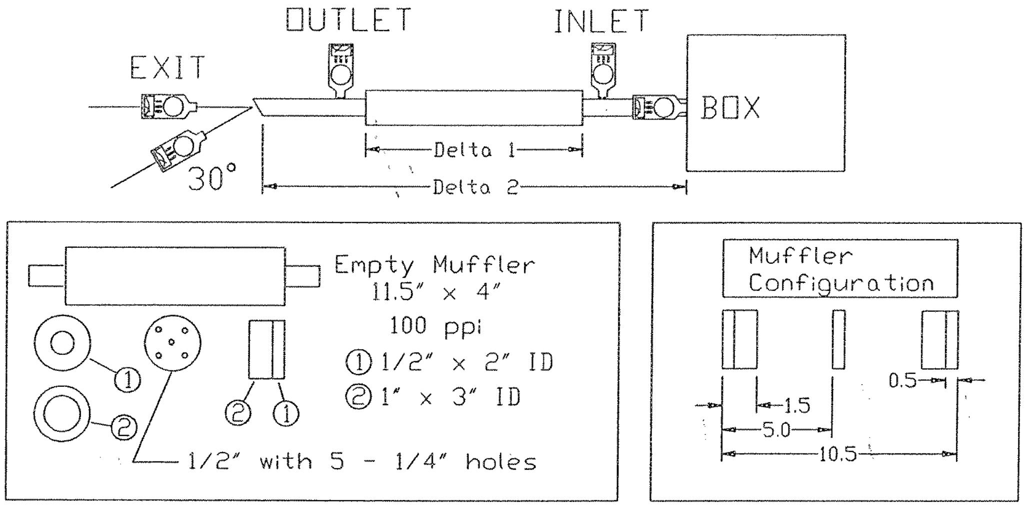
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	104	79	80	8	31
700	1429	110	114	102	72	74	12	38
750	1333	110	115	103	72	73	12	38
800	1250	110	117	105	67	71	12	43
850	1176	110	117	105	68	71	12	42
900	1111	110	113	101	64	68	12	46
950	1053	110	111	98	72	74	13	38
1000	1000	110	107	98	75	77	9	35
1100	909	110	108	97	71	74	11	39
1200	833	110	117	97	78	83	20	32
1300	769	110	116	91	70	71	25	40
1400	714	110	124	97	72	72	27	38
1500	667	110	124	94	60	68	30	50
1600	625	110	114	94	58	63	20	52
1700	588	110	115	97	56	63	18	54
1800	556	110	117	102	68	72	15	42
1900	526	110	111	94	62	62	17	48
2000	500	110	104	85	62	56	19	48
2200	455	110	99	82	56	60	17	54
2400	417	110	93	77	59	60	16	51
2600	385	110	97	67	58	59	30	52
2800	357	110	95	66	57	59	29	53
3000	333	110	93	62	57	58	31	53



CONFIGURATION #7

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	105	92	62	62	13	48
60	16667	110	105	94	55-61	55-61	11	55
80	12500	110	105	93	63	63	12	47
100	10000	110	105	94	60	60	11	50
120	8333	110	106	97	56	56	9	54
140	7143	110	107	100	68	68	7	42
160	6250	110	105	101	68	68	4	42
180	5556	110	106	100	70	69	6	40
200	5000	110	111'	102	68	69	9	42
240	4167	110	106	102	66	66	4	44
280	3571	110	106	103	73	74	3	37
320	3125	110	110	98	62	64	12	48
360	2778	110	114	102	64	70	12	46
400	2500	110	123	113	75	77	10	35
450	2222	110	118	112	78	77	6	32
500	2000	110	113	112	72	72	1	38
550	1818	110	115	119	78	77	-4	32
600	1667	110	113	111	76	77	2	34

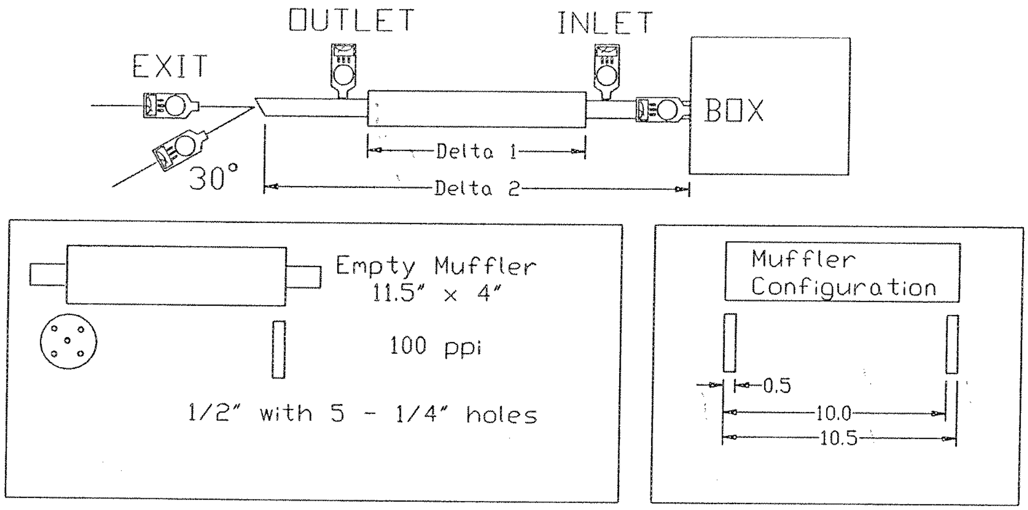
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	111	83	85	1	27
700	1429	110	114	118	74	77	-4	36
750	1333	110	112	112	76	76	0	34
800	1250	110	116	111	71	73	5	39
850	1176	110	126	119	80	84	7	30
900	1111	110	115	107	70	72	8	40
950	1053	110	107	103	65	66	4	45
1000	1000	110	102	102	77	75	0	33
1100	909	110	112	111	82	83	1	28
1200	833	110	121	111	90	92	10	20
1300	769	110	117	100	79	81	17	31
1400	714	110	122	111	83	84	11	27
1500	667	110	125	106	70	70	19	40
1600	625	110	115	103	65	66	12	45
1700	588	110	120	112	76	76	8	34
1800	556	110	118	118	84	86	0	26
1900	526	110	107	108	77	78	-1	33
2000	500	110	104	102	72	70	2	38
2200	455	110	96	95	69	70	1	41
2400	417	110	93	92	75	77	1	35
2600	385	110	96	85	76	77	11	34
2800	357	110	96	84	74	74	12	36
3000	333	110	86	77	66	66	9	44



CONFIGURATION #8

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	107	95	62	63	12	48
60	16667	110	107	100	58-62	58-62	7	52
80	12500	110	107	97	64	65	10	46
100	10000	110	108	99	64	64	9	46
120	8333	110	108	102	59-61	59-61	6	51
140	7143	110	106	103	71	70	3	39
160	6250	110	103	101	68	68	2	42
180	5556	110	107	100	70	69	7	40
200	5000	110	108	100	66	67	8	44
240	4167	110	106	100	64	64	6	46
280	3571	110	107	100	73	74	7	37
320	3125	110	111	100	64	64	11	46
360	2778	110	116	105	70	74	11	40
400	2500	110	123	113	72	76	10	38
450	2222	110	115	109	74	74	6	36
500	2000	110	113	111	71	71	2	39
550	1818	110	114	114	72	71	0	38
600	1667	110	112	111	74	76	1	36

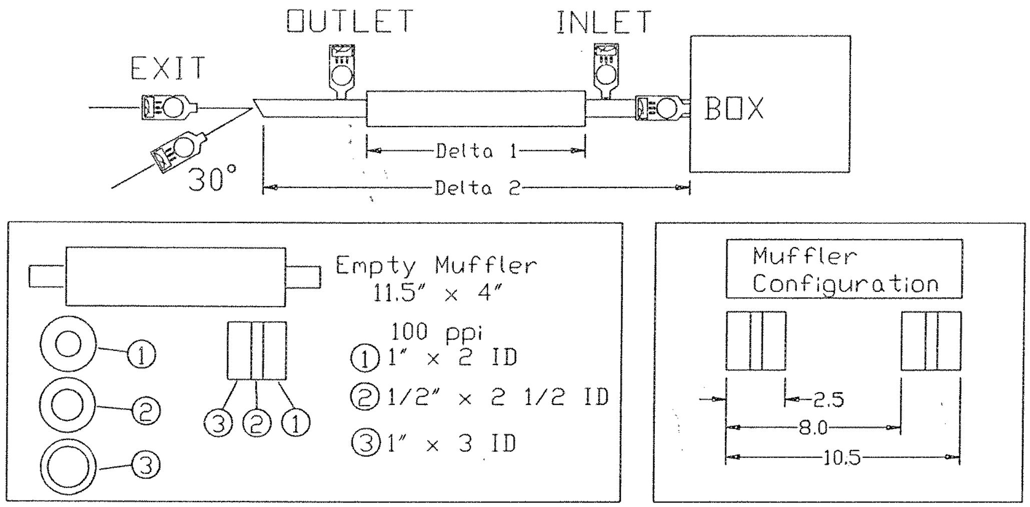
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	112	83	84	0	27
700	1429	110	113	114	72	74	-1	38
750	1333	110	114	112	74	76	2	36
800	1250	110	118	113	72	76	5	38
850	1176	110	116	110	70	74	6	40
900	1111	110	107	103	65	66	4	45
950	1053	110	101	101	64	64	0	46
1000	1000	110	98	99	81	77	-1	29
1100	909	110	117	109	82	82	8	28
1200	833	110	121	107	87	88	14	23
1300	769	110	117	96	78	79	21	32
1400	714	110	123	109	72	73	14	38
1500	667	110	125	104	68	69	21	42
1600	625	110	117	104	65	68	13	45
1700	588	110	118	110	72	74	8	38
1800	556	110	113	108	72	74	5	38
1900	526	110	106	107	73	76	-1	37
2000	500	110	102	102	69	69	0	41
2200	455	110	95	91	67	68	4	43
2400	417	110	102	92	75	77	10	35
2600	385	110	99	85	76	77	14	34
2800	357	110	99	87	76	77	12	34
3000	333	110	85	79	66	65	6	44



CONFIGURATION #9

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	105	91	60	60	14	50
60	16667	110	105	93	57	57	12	53
80	12500	110	105	91	61	62	14	49
100	10000	110	106	93	59	59	13	51
120	8333	110	106	95	57	57	11	53
140	7143	110	107	98	66	67	9	44
160	6250	110	107	101	68	67	6	42
180	5556	110	107	100	70	71	7	40
200	5000	110	111	101	69	69	10	41
240	4167	110	106	102	68	68	4	42
280	3571	110	106	100	72	74	6	38
320	3125	110	109	98	64	64	11	46
360	2778	110	113	102	68	72	11	42
400	2500	110	121	111	74	76	10	36
450	2222	110	118	112	77	78	6	33
500	2000	110	113	112	76	75	1	34
550	1818	110	113	112	70	70	1	40
600	1667	110	113	109	71	74	4	39

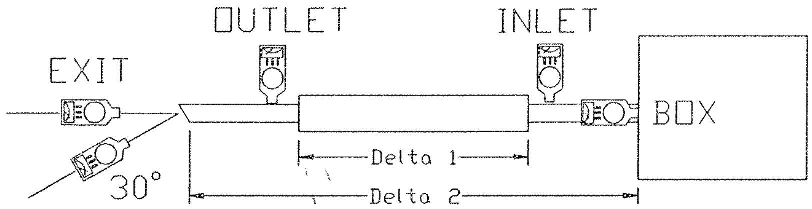
Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	108	82	83	4	28
700	1429	110	114	116	75	77	-2	35
750	1333	110	112	112	76	74	0	34
800	1250	110	116	110	70	73	6	40
850	1176	110	123	115	75	78	8	35
900	1111	110	116	107	72	75	9	38
950	1053	110	108	103	66	68	5	44
1000	1000	110	103	102	83	80	1	27
1100	909	110	109	107	80	81	2	30
1200	833	110	122	107	86	87	15	24
1300	769	110	117	94	76	75	23	34
1400	714	110	123	113	87	87	10	23
1500	667	110	125	105	74	73	20	36
1600	625	110	115	104	63	68	11	47
1700	588	110	119	112	72	72	7	38
1800	556	110	115	113	76	78	2	34
1900	526	110	106	105	74	75	1	36
2000	500	110	104	108	77	77	-4	33
2200	455	110	97	98	73	75	-1	37
2400	417	110	94	87	69	72	7	41
2600	385	110	97	85	76	78	12	34
2800	357	110	94	86	75	76	8	35
3000	333	110	85	74	61	61	11	49

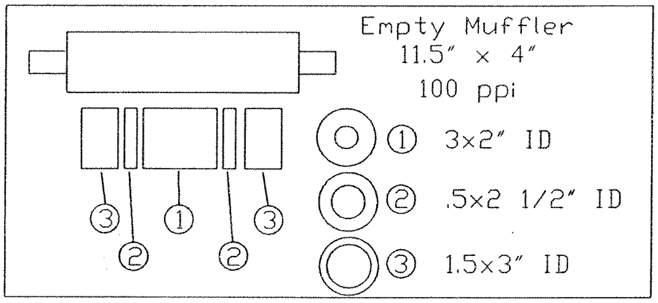


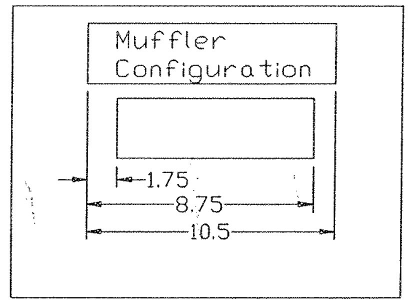
CONFIGURATION #10

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	105	93	61	61	12	49
60	16667	110	105	95	59	60	10	51
80	12500	110	106	94	62	63	12	48
100	10000	110	106	95	60	60	11	50
120	8333	110	106	97	61	61	9	49
140	7143	110	107	101	68	68	6	42
160	6250	110	105	101	65	64	4	45
180	5556	110	108	100	69	70	8	41
200	5000	110	109	100	67	67	9	43
240	4167	110	106	100	64	64	6	46
280	3571	110	107	101	72	74	6	38
320	3125	110	111	99	63	64	12	47
360	2778	110	116	104	70	73	12	40
400	2500	110	124	114	74	76	10	36
450	2222	110	116	109	75	75	7	35
500	2000	110	112	110	71	71	2	39
550	1818	110	113	115	73	73	-2	37
600	1667	110	112	111	73	75	1	37

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	111	83	84	1	27
700	1429	110	114	116	76	76	-2	34
750	1333	110	113	113	77	74	0	33
800	1250	110	116	112	71	75	4	39
850	1176	110	119	114	72	76	5	38
900	1111	110	111	105	70	73	6	40
950	1053	110	104	101	63	68	3	47
1000	1000	110	103	100	84	82	3	26
1100	909	110	114	107	80	82	7	30
1200	833	110	121	107	86	88	14	24
1300	769	110	117	96	77	78	21	33
1400	714	110	125	105	78	79	20	32
1500	667	110	125	101	70	68	24	40
1600	625	110	117	105	66	68	12	44
1700	588	110	119	112	72	73	7	38
1800	556	110	114	111	71	76	3	39
1900	526	110	105	106	72	73	-1	38
2000	500	110	102	101	70	68	1	40
2200	455	110	97	93	67	70	4	43
2400	417	110	101	92	70	75	9	40
2600	385	110	98	82	72	74	16	38
2800	357	110	98	84	72	73	14	38
3000	333	110	77	72	52	59	5	58



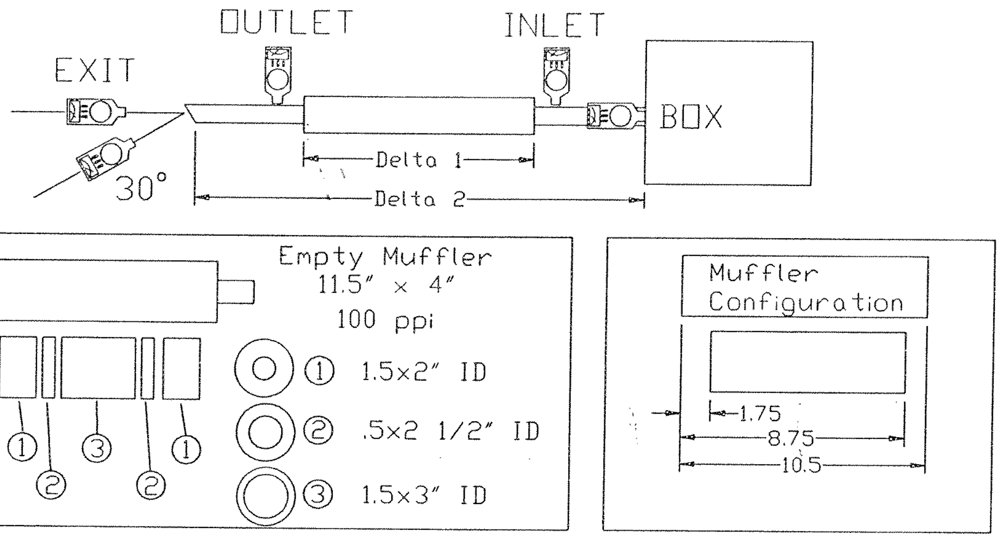




CONFIGURATION #11

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	105	92	61	61	13	49
60	16667	110	105	95	56-61	56-61	10	54
80	12500	110	106	93	63	63	13	47
100	10000	110	106	94	60	60	12	50
120	8333	110	106	97	58-63	58-63	9	52
140	7143	110	107	100	68	68	7	42
160	6250	110	106	102	69	69	4	41
180	5556	110	107	100	68	68	7	42
200	5000	110	108	101	66	67	7	44
240	4167	110	106	101	65	64	5	45
280	3571	110	108	99	70	71	9	40
320	3125	110	111	100	69	71	11	41
360	2778	110	115	105	72	74	10	38
400	2500	110	118	110	73	74	8	37
450	2222	110	114	110	76	75	4	34
500	2000	110	115	111	70	70	4	40
550	1818	110	113	110	70	72	3	40
600	1667	110	111	108	72	73	3	38

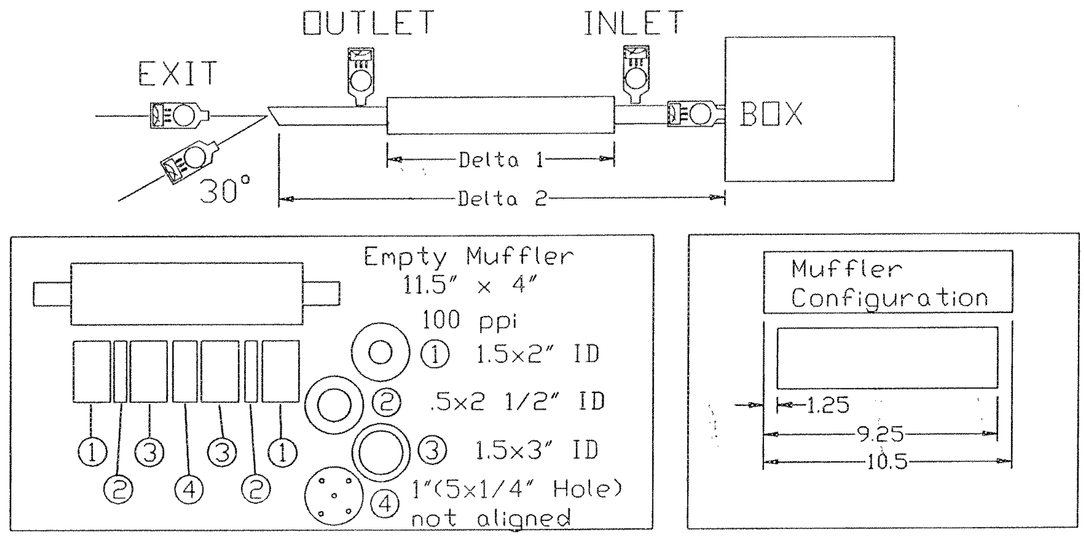
Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	112	78	79	-1	32
700	1429	110	113	110	78	78	3	32
750	1333	110	114	108	71	74	6	39
800	1250	110	121	112	74	76	9	36
850	1176	110	117	107	71	72	10	39
900	1111	110	111	102	64	66	9	46
950	1053	110	104	97	67	67	7	43
1000	1000	110	103	97	79	79	6	31
1100	909	110	110	101	75	76	9	35
1200	833	110	122	107	89	90	15	21
1300	769	110	118	96	78	78	22	32
1400	714	110	125	99	65	70	26	45
1500	667	110	125	99	62	65	26	48
1600	625	110	116	102	61	60	14	49
1700	588	110	119	109	68	71	10	42
1800	556	110	116	109	69	73	7	41
1900	526	110	106	103	69	69	3	41
2000	500	110	102	98	67	69	4	43
2200	455	110	94	93	68	70	1	42
2400	417	110	97	85	69	72	12	41
2600	385	110	100	82	71	73	18	39
2800	357	110	103	86	76	76	17	34
3000	333	110	83	77	67	65	6	43



CONFIGURATION #12

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	106	94	62	62	12	48
60	16667	110	106	97	62	62	9	48
80	12500	110	106	95	64	64	11	46
100	10000	110	106	96	62	62	10	48
120	8333	110	107	99	60-64	60-64	8	50
140	7143	110	107	102	68	68	5	42
160	6250	110	105	101	68	68	4	42
180	5556	110	107	100	68	68	7	42
200	5000	110	107	100	65	66	7	45
240	4167	110	105	100	64	64	5	46
280	3571	110	108	99	70	71	9	40
320	3125	110	111	100	69	71	11	41
360	2778	110	116	106	72	75	10	38
400	2500	110	119	111	73	74	8	37
450	2222	110	114	109	76	75	5	34
500	2000	110	115	111	72	72	4	38
550	1818	110	114	111	72	74	3	38
600	1667	110	113	109	68	70	4	42

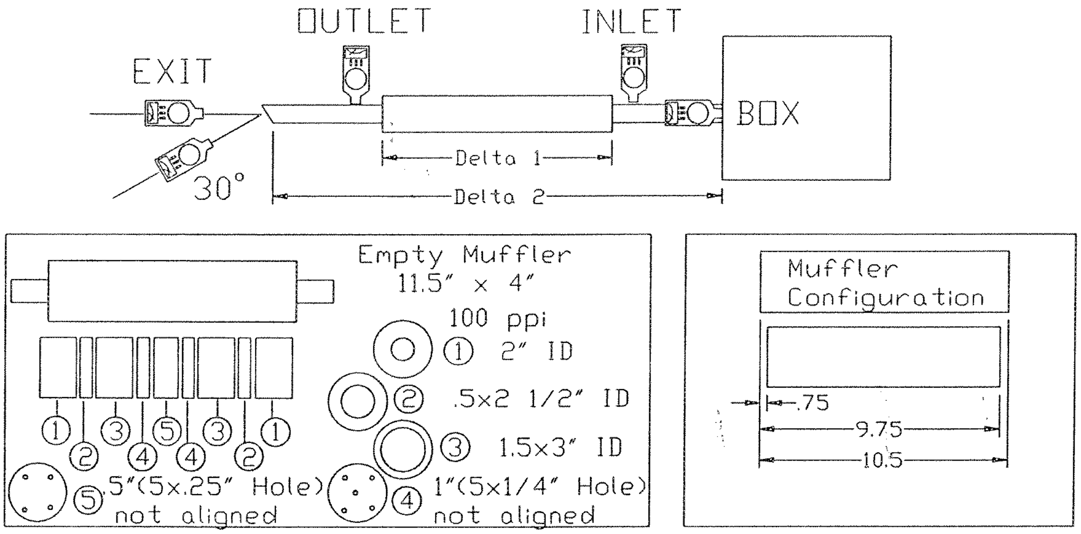
Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	112	78	78	0	32
700	1429	110	114	112	78	78	2	32
750	1333	110	115	109	71	74	6	39
800	1250	110	119	112	73	75	7	37
850	1176	110	118	109	73	75	9	37
900	1111	110	112	103	66	66	9	44
950	1053	110	106	101	70	66	5	40
1000	1000	110	104	98	78	78	6	32
1100	909	110	108	99	69	69	9	41
1200	833	110	121	106	87	88	15	23
1300	769	110	118	95	78	78	23	32
1400	714	110	124	98	64	64	26	46
1500	667	110	125	97	65	65	28	45
1600	625	110	117	102	64	64	15	46
1700	588	110	121	108	67	68	13	43
1800	556	110	115	106	67	68	9	43
1900	526	110	105	101	69	68	4	41
2000	500	110	102	97	67	69	5	43
2200	455	110	95	93	67	70	2	43
2400	417	110	98	86	69	74	12	41
2600	385	110	100	84	74	75	16	36
2800	357	110	103	88	78	78	15	32
3000	333	110	91	84	73	75	7	37



CONFIGURATION #13

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	105	92	61	61	13	49
60	16667	110	105	94	59	59	11	51
80	12500	110	105	92	62	62	13	48
100	10000	110	106	94	60	60	12	50
120	8333	110	104	93	58	57	11	52
140	7143	110	107	100	67	67	7	43
160	6250	110	105	101	67	68	4	43
180	5556	110	106	100	67	68	6	43
200	5000	110	107	100	65	66	7	45
240	4167	110	106	99	63	62	7	47
280	3571	110	108	98	70	71	10	40
320	3125	110	111	100	69	71	11	41
360	2778	110	114	104	72	73	10	38
400	2500	110	117	109	72	73	8	38
450	2222	110	115	108	75	74	7	35
500	2000	110	113	109	69	69	4	41
550	1818	110	112	108	70	71	4	40
600	1667	110	112	107	66	68	5	44

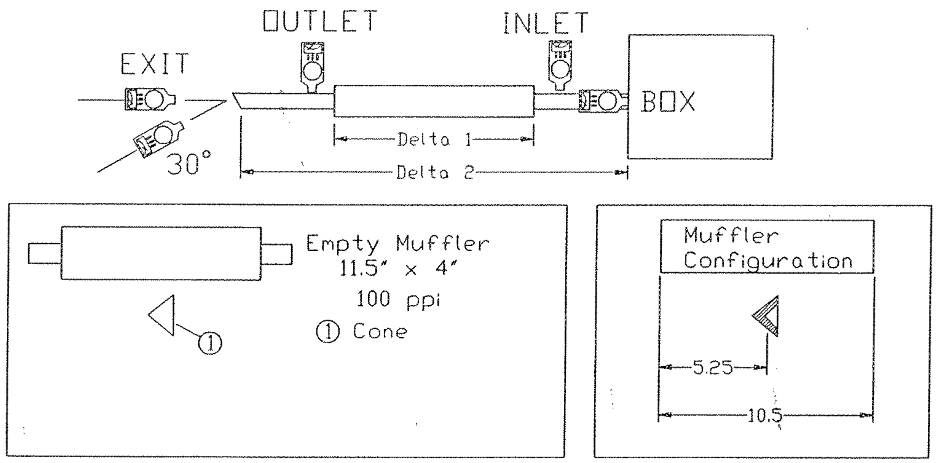
Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	111	76	77	0	34
700	1429	110	112	109	76	76	3	34
750	1333	110	114	108	70	73	6	40
800	1250	110	118	111	70	73	7	40
850	1176	110	116	108	72	73	8	38
900	1111	110	109	102	64	64	7	46
950	1053	110	107	99	67	66	8	43
1000	1000	110	105	98	74	76	7	36
1100	909	110	108	99	72	72	9	38
1200	833	110	119	104	85	86	15	25
1300	769	110	117	96	77	77	21	33
1400	714	110	124	98	64	68	26	46
1500	667	110	125	96	64	64	29	46
1600	625	110	116	101	66	66	15	44
1700	588	110	119	103	59	66	16	51
1800	556	110	115	101	62	66	14	48
1900	526	110	106	99	65	65	7	45
2000	500	110	102	94	63	66	8	47
2200	455	110	93	87	65	66	6	45
2400	417	110	97	83	66	70	14	44
2600	385	110	100	81	71	72	19	39
2800	357	110	98	81	69	68	17	41
3000	333	110	85	77	66	68	8	44



CONFIGURATION #14

Hz	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	105	92	61	61	13	49
60	16667	110	106	94	60	60	12	50
80	12500	110	106	93	63	63	13	47
100	10000	110	106	95	60	60	11	50
120	8333	110	106	97	58-62	58-62	9	52
140	7143	110	106	101	68	67	5	42
160	6250	110	104	100	68	68	4	42
180	5556	110	105	98	67	67	7	43
200	5000	110	106	98	65	66	8	45
240	4167	110	106	97	62	61	9	48
280	3571	110	107	97	70	70	10	40
320	3125	110	111	100	67	70	11	43
360	2778	110	114	103	71	73	11	39
400	2500	110	116	107	70	71	9	40
450	2222	110	116	108	75	73	8	35
500	2000	110	114	107	68	69	7	42
550	1818	110	112	106	67	69	6	43
600	1667	110	111	106	64	65	5	46

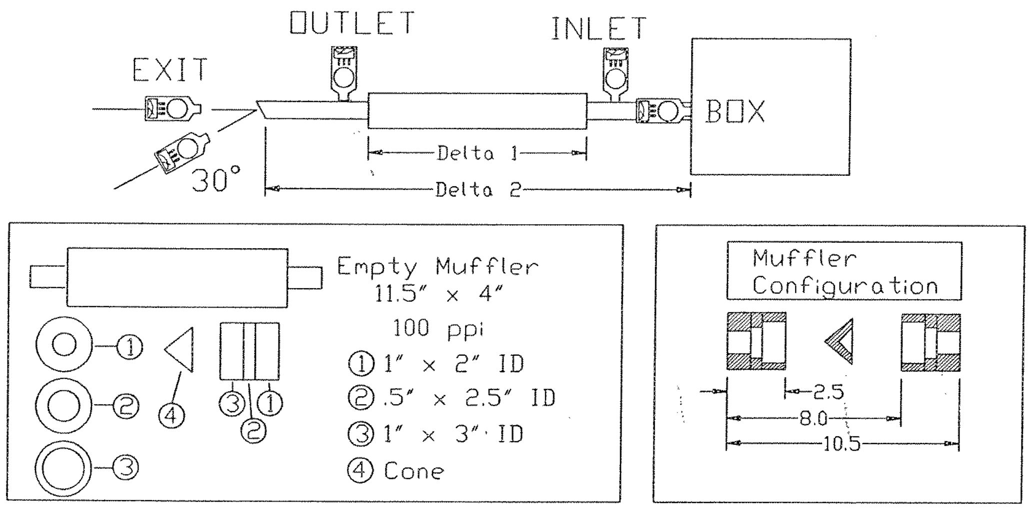
Hz	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	110	66	68	1	44
700	1429	110	111	107	66	65	4	44
750	1333	110	114	107	71	73	7	39
800	1250	110	118	109	70	71	9	40
850	1176	110	114	104	68	70	10	42
900	1111	110	109	110	61	62	-1	49
950	1053	110	106	98	70	67	8	40
1000	1000	110	106	98	67	71	8	43
1100	909	110	109	98	68	68	11	42
1200	833	110	119	101	82	84	18	28
1300	769	110	117	95	75	75	22	35
1400	714	110	125	99	64	67	26	46
1500	667	110	125	97	60	59	28	50
1600	625	110	116	99	62	64	17	48
1700	588	110	118	101	59	66	17	51
1800	556	110	116	101	62	66	15	48
1900	526	110	105	97	65	65	8	45
2000	500	110	102	93	61	66	9	49
2200	455	110	94	86	61	64	8	49
2400	417	110	97	78	64	67	19	46
2600	385	110	99	76	66	68	23	44
2800	357	110	102	80	69	71	22	41
3000	333	110	81	71	57	58	10	53



CONFIGURATION #15

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	104	92	59	59	12	51
60	16667	110	104	94	61	61	10	49
80	12500	110	104	93	60	60	11	50
100	10000	110	105	94	60	60	11	50
120	8333	110	105	97	60	61	8	50
140	7143	110	107	100	66	66	7	44
160	6250	110	107	103	67	67	4	43
180	5556	110	110	103	66	66	7	44
200	5000	110	110	103	70	71	7	40
240	4167	110	106	102	74	73	4	36
280	3571	110	109	108	69	69	1	41
320	3125	110	111	100	66	66	11	44
360	2778	110	117	105	59	62	12	51
400	2500	110	126	119	82	82	7	28
450	2222	110	117	110	67	68	7	43
500	2000	110	109	110	71	71	-1	39
550	1818	110	113	121	84	84	-8	26
600	1667	110	112	113	79	80	-1	31

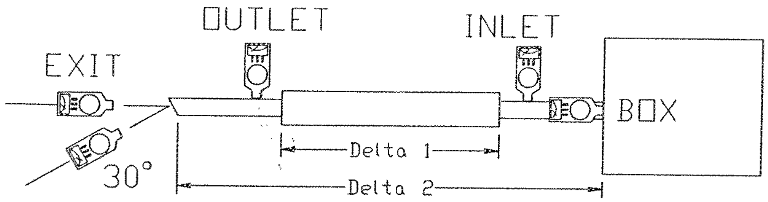
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	112	82	82	-1	28
700	1429	110	114	123	87	88	-9	23
750	1333	110	112	115	77	79	-3	33
800	1250	110	118	116	76	78	2	34
850	1176	110	119	115	74	76	4	36
900	1111	110	107	104	64	67	3	46
950	1053	110	97	100	65	73	-3	45
1000	1000	110	96	98	80	76	-2	30
1100	909	110	122	114	89	89	8	21
1200	833	110	122	112	93	94	10	17
1300	769	110	117	100	80	81	17	30
1400	714	110	122	114	83	85	8	27
1500	667	110	126	109	62	70	17	48
1600	625	110	119	102	62	64	17	48
1700	588	110	126	117	81	83	9	29
1800	556	110	110	116	82	85	-6	28
1900	526	110	103	109	77	78	-6	33
2000	500	110	103	110	78	77	-7	32
2200	455	110	93	89	66	65	4	44
2400	417	110	109	100	84	87	9	26
2600	385	110	98	93	85	86	5	25
2800	357	110	95	86	76	75	9	34
3000	333	110	108	111	101	101	-3	9

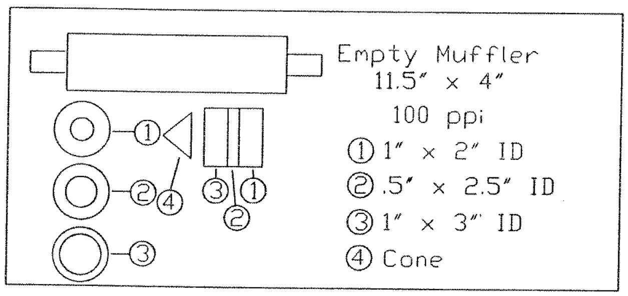


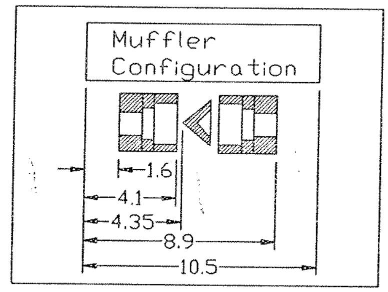
CONFIGURATION #16

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	$\Delta 1$	$\Delta 2$
40	25000	110	104	92	59	59	12	51
60	16667	110	104	94	61	61	10	49
80	12500	110	104	92	60	60	12	50
100	10000	110	105	94	60	60	11	50
120	8333	110	105	97	61	61	8	49
140	7143	110	107	100	66	65	7	44
160	6250	110	106	101	66	65	5	44
180	5556	110	110	102	64	65	8	46
200	5000	110	109	102	69	70	7	41
240	4167	110	106	101	74	72	5	36
280	3571	110	108	102	74	74	6	36
320	3125	110	111	101	67	67	10	43
360	2778	110	118	107	64	66	11	46
400	2500	110	123	114	77	77	9	33
450	2222	110	115	110	69	71	5	41
500	2000	110	110	112	73	73	-2	37
550	1818	110	113	115	78	79	-2	32
600	1667	110	112	111	76	76	1	34

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	112	81	79	-1	29
700	1429	110	113	117	82	83	-4	28
750	1333	110	113	112	74	77	1	36
800	1250	110	118	114	76	78	4	34
850	1176	110	117	112	72	73	5	38
900	1111	110	106	105	66	69	1	44
950	1053	110	101	101	61	67	0	49
1000	1000	110	102	99	74	70	3	36
1100	909	110	114	108	79	78	6	31
1200	833	110	121	107	86	87	14	24
1300	769	110	117	99	79	78	18	31
1400	714	110	124	107	74	77	17	36
1500	667	110	126	105	55	68	21	55
1600	625	110	119	104	62	65	15	48
1700	588	110	119	109	75	76	10	35
1800	556	110	118	111	76	80	7	34
1900	526	110	102	102	69	71	0	41
2000	500	110	101	99	70	69	2	40
2200	455	110	95	86	63	63	9	47
2400	417	110	103	90	74	77	13	36
2600	385	110	99	81	72	73	18	38
2800	357	110	87	73	64	63	14	46
3000	333	110	102	93	84	84	9	26



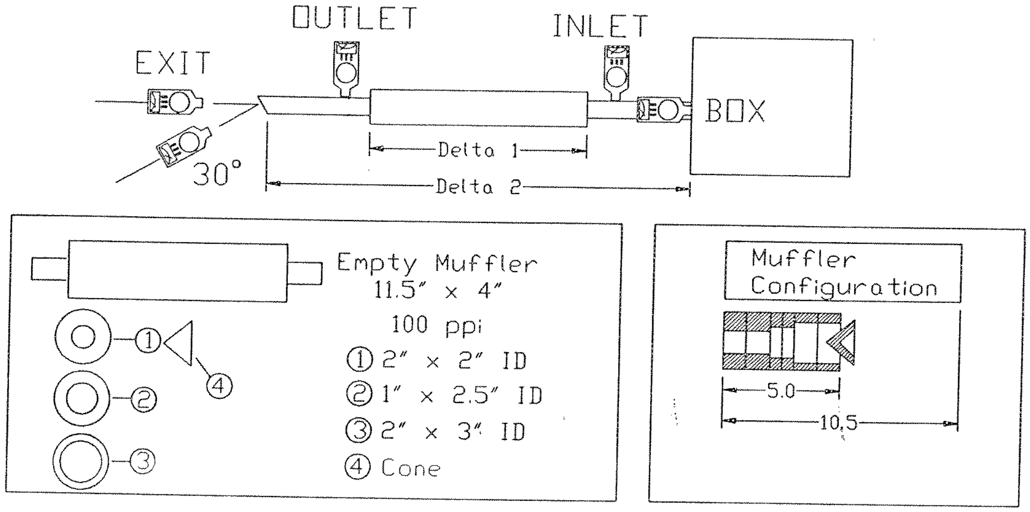




CONFIGURATION #17

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	104	92	59	59	12	51
60	16667	110	104	94	60	60	10	50
80	12500	110	104	92	59	59	12	51
100	10000	110	105	94	60	60	11	50
120	8333	110	105	97	60	60	8	50
140	7143	110	107	100	65	65	7	45
160	6250	110	106	101	65	65	5	45
180	5556	110	109	101	63	64	8	47
200	5000	110	109	102	70	70	7	40
240	4167	110	105	102	74	72	3	36
280	3571	110	108	101	62	63	7	48
320	3125	110	111	101	65	66	10	45
360	2778	110	117	107	64	66	10	46
400	2500	110	122	113	74	75	9	36
450	2222	110	115	111	69	71	4	41
500	2000	110	113	113	75	75	0	35
550	1818	110	113	113	77	77	0	33
600	1667	110	112	111	77	77	1	33

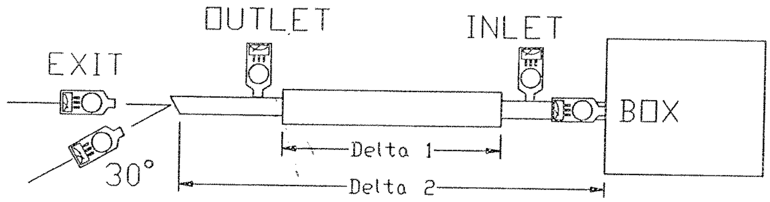
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	113	81	79	-2	29
700	1429	110	114	112	79	80	2	31
750	1333	110	114	110	73	75	4	37
800	1250	110	120	113	73	75	7	37
850	1176	110	119	112	73	76	7	37
900	1111	110	109	105	65	69	4	45
950	1053	110	103	101	68	73	2	42
1000	1000	110	101	99	79	76	2	31
1100	909	110	107	103	75	74	4	35
1200	833	110	122	109	90	90	13	20
1300	769	110	118	99	78	79	19	32
1400	714	110	123	103	67	72	20	43
1500	667	110	126	101	57	68	25	53
1600	625	110	118	99	67	65	19	43
1700	588	110	121	109	72	74	12	38
1800	556	110	119	111	77	79	8	33
1900	526	110	105	102	69	70	3	41
2000	500	110	101	96	65	60	5	45
2200	455	110	91	84	60	64	7	50
2400	417	110	101	90	74	76	11	36
2600	385	110	101	82	72	75	19	38
2800	357	110	92	79	69	69	13	41
3000	333	110	99	98	88	87	1	22

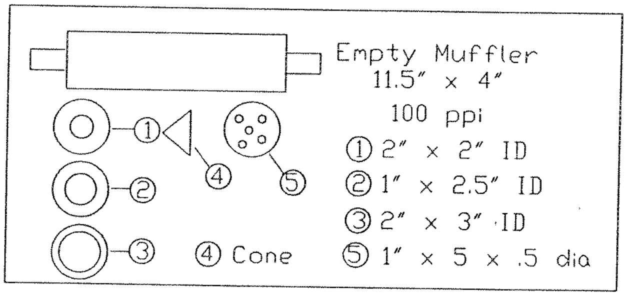


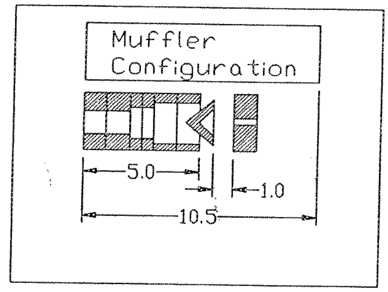
CONFIGURATION #18

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	104	92	59	59	12	51
60	16667	110	104	95	61	61	9	49
80	12500	110	104	93	60	60	11	50
100	10000	110	105	94	60	60	11	50
120	8333	110	105	97	60	61	8	50
140	7143	110	107	100	66	65	7	44
160	6250	110	106	102	66	66	4	44
180	5556	110	110	102	64	65	8	46
200	5000	110	108	101	69	70	7	41
240	4167	110	105	101	74	73	4	36
280	3571	110	108	103	66	66	5	44
320	3125	110	112	101	65	66	11	45
360	2778	110	118	108	67	69	10	43
400	2500	110	121	111	74	75	10	36
450	2222	110	113	108	73	74	5	37
500	2000	110	111	111	71	70	0	39
550	1818	110	114	117	79	79	-3	31
600	1667	110	112	112	77	78	0	33

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	114	81	80	-3	29
700	1429	110	114	113	80	81	1	30
750	1333	110	114	111	72	75	3	38
800	1250	110	119	113	75	78	6	35
850	1176	110	116	110	71	70	6	39
900	1111	110	107	103	65	68	4	45
950	1053	110	101	100	61	73	1	49
1000	1000	110	101	99	77	66	2	33
1100	909	110	114	108	80	78	6	30
1200	833	110	121	107	86	86	14	24
1300	769	110	118	100	78	80	18	32
1400	714	110	124	105	73	76	19	37
1500	667	110	126	103	56	65	23	54
1600	625	110	119	101	63	65	18	47
1700	588	110	119	109	74	75	10	36
1800	556	110	118	112	78	82	6	32
1900	526	110	103	103	72	73	0	38
2000	500	110	101	99	71	70	2	39
2200	455	110	95	85	63	62	10	47
2400	417	110	103	91	76	79	12	34
2600	385	110	100	82	74	75	18	36
2800	357	110	87	75	65	64	12	45
3000	333	110	103	99	89	89	4	21





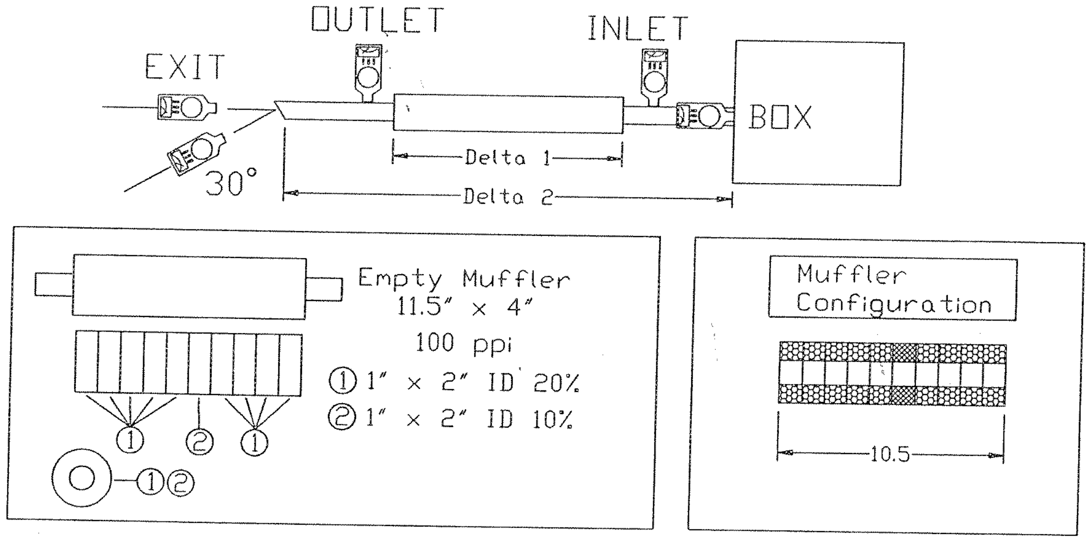


CONFIGURATION #19

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	104	92	58	58	12	52
60	16667	110	104	94	60	60	10	50
80	12500	110	105	92	60	59	13	50
100	10000	110	105	94	60	60	11	50
120	8333	110	105	97	60	60	8	50
140	7143	110	107	99	65	66	8	45
160	6250	110	106	101	65	66	5	45
180	5556	110	108	101	63	64	7	47
200	5000	110	108	101	70	70	7	40
240	4167	110	105	100	73	71	5	37
280	3571	110	108	100	61	61	8	49
320	3125	110	111	101	65	66	10	45
360	2778	110	118	107	67	69	11	43
400	2500	110	120	111	72	73	9	38
450	2222	110	113	109	67	67	4	43
500	2000	110	112	111	69	69	1	41
550	1818	110	112	112	76	76	0	34
600	1667	110	111	111	73	75	0	37

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	113	82	81	-2	28
700	1429	110	112	112	80	81	0	30
750	1333	110	114	110	73	76	4	37
800	1250	110	118	112	74	76	6	36
850	1176	110	115	108	70	70	7	40
900	1111	110	107	102	63	67	5	47
950	1053	110	103	100	70	74	3	40
1000	1000	110	104	99	69	67	5	41
1100	909	110	110	103	76	75	7	34
1200	833	110	121	106	86	87	15	24
1300	769	110	117	97	76	76	20	34
1400	714	110	121	102	66	70	19	44
1500	667	110	126	107	65	67	19	45
1600	625	110	120	97	59	54	23	51
1700	588	110	120	104	68	70	16	42
1800	556	110	118	109	73	77	9	37
1900	526	110	106	101	69	67	5	41
2000	500	110	102	95	65	66	7	45
2200	455	110	96	85	60	65	11	50
2400	417	110	103	89	73	76	14	37
2600	385	110	101	81	72	74	20	38
2800	357	110	87	75	64	65	12	46
3000	333	110	107	100	91	89	7	19

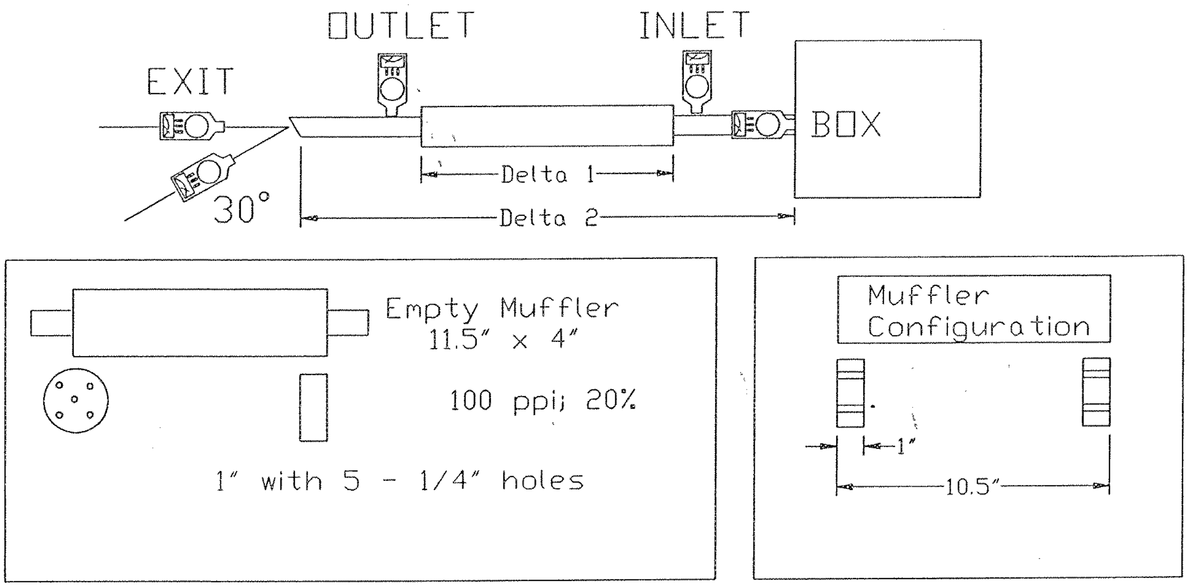
CONFIGURATION NUMBER 20
FEBRUARY 8, 1997



CONFIGURATION #20

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	104	94	61	61	10	49
60	16667	110	105	98	63	63	7	47
80	12500	110	105	95	62	62	10	48
100	10000	110	106	97	62	61	9	48
120	8333	110	107	100	65	65	7	45
140	7143	110	107	103	67	67	4	43
160	6250	110	103	102	66	65	1	44
180	5556	110	110	101	67	68	9	43
200	5000	110	108	101	69	69	7	41
240	4167	110	105	101	72	73	4	38
280	3571	110	109	104	67	68	5	43
320	3125	110	111	101	62	61	10	48
360	2778	110	118	107	72	73	11	38
400	2500	110	124	115	78	78	9	32
450	2222	110	115	110	70	71	5	40
500	2000	110	110	113	75	76	-3	35
550	1818	110	112	115	79	80	-3	31
600	1667	110	111	110	76	77	1	34

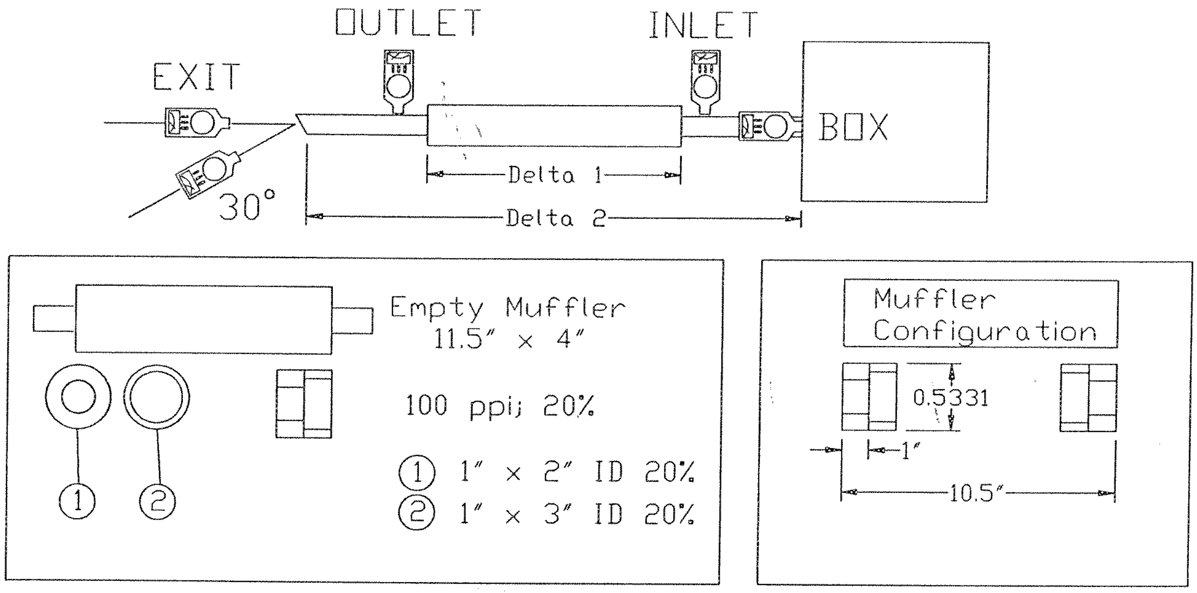
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	110	112	79	78	-2	31
700	1429	110	113	118	84	84	-5	26
750	1333	110	112	113	79	81	-1	31
800	1250	110	118	115	77	80	3	33
850	1176	110	117	113	76	76	4	34
900	1111	110	107	107	70	71	0	40
950	1053	110	101	103	65	65	-2	45
1000	1000	110	103	103	82	79	0	28
1100	909	110	110	107	80	82	3	30
1200	833	110	121	107	86	87	14	24
1300	769	110	117	101	81	82	16	29
1400	714	110	123	109	77	79	14	33
1500	667	110	126	104	62	66	22	48
1600	625	110	118	102	67	66	16	43
1700	588	110	118	107	75	76	11	35
1800	556	110	117	108	77	80	9	33
1900	526	110	102	100	66	69	2	44
2000	500	110	100	97	69	70	3	41
2200	455	110	95	83	59	62	12	51
2400	417	110	101	84	71	74	17	39
2600	385	110	98	75	66	67	23	44
2800	357	110	85	67	58	58	18	52
3000	333	110	103	89	78	81	14	32



CONFIGURATION #21

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	105	92	61	61	13	49
60	16667	110	105	97	63	63	8	47
80	12500	110	107	93	62	62	14	48
100	10000	110	107	95	62	62	12	48
120	8333	110	107	99	65	65	8	45
140	7143	110	106	100	66	66	6	44
160	6250	110	102	98	62	60	4	48
180	5556	110	104	98	67	67	6	43
200	5000	110	106	98	67	66	8	43
240	4167	110	106	99	74	74	7	36
280	3571	110	109	102	70	70	7	40
320	3125	110	111	99	60	59	12	50
360	2778	110	115	104	75	76	11	35
400	2500	110	118	109	65	64	9	45
450	2222	110	113	109	75	75	4	35
500	2000	110	111	110	73	76	1	37
550	1818	110	110	107	72	74	3	38
600	1667	110	110	107	73	74	3	37

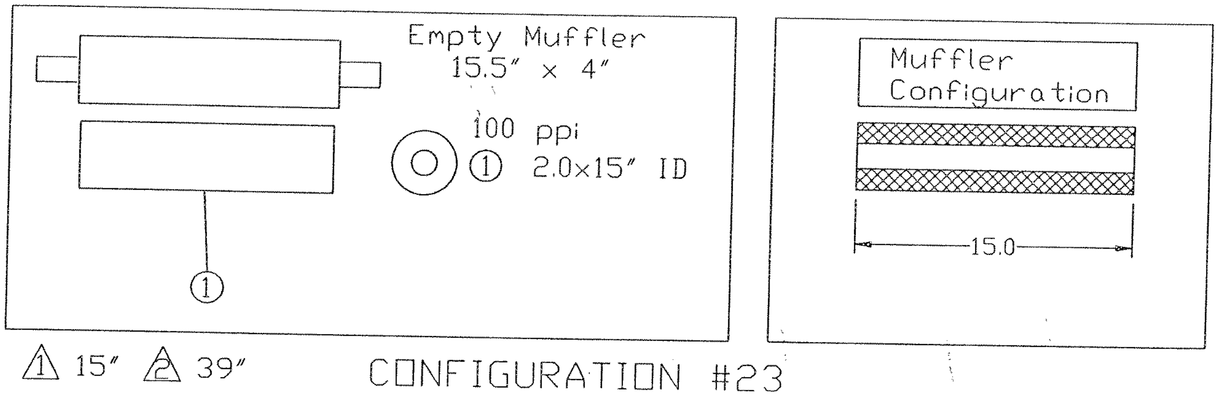
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	110	110	79	78	0	31
700	1429	110	111	113	84	83	-2	26
750	1333	110	111	110	77	79	1	33
800	1250	110	114	110	71	74	4	39
850	1176	110	115	110	72	73	5	38
900	1111	110	111	106	67	70	5	43
950	1053	110	108	103	68	68	5	42
1000	1000	110	108	103	82	82	5	28
1100	909	110	111	102	78	77	9	32
1200	833	110	119	99	77	78	20	33
1300	769	110	116	95	77	77	21	33
1400	714	110	121	111	80	81	10	30
1500	667	110	126+	110	64	67	16	46
1600	625	110	117	100	66	69	17	44
1700	588	110	116	105	74	75	11	36
1800	556	110	116	101	78	79	15	32
1900	526	110	107	100	68	68	7	42
2000	500	110	103	96	70	68	7	40
2200	455	110	98	91	68	70	7	42
2400	417	110	95	82	70	72	13	40
2600	385	110	99	79	71	73	20	39
2800	357	110	90	73	65	64	17	45
3000	333	110	98	80	73	71	18	37



CONFIGURATION #22

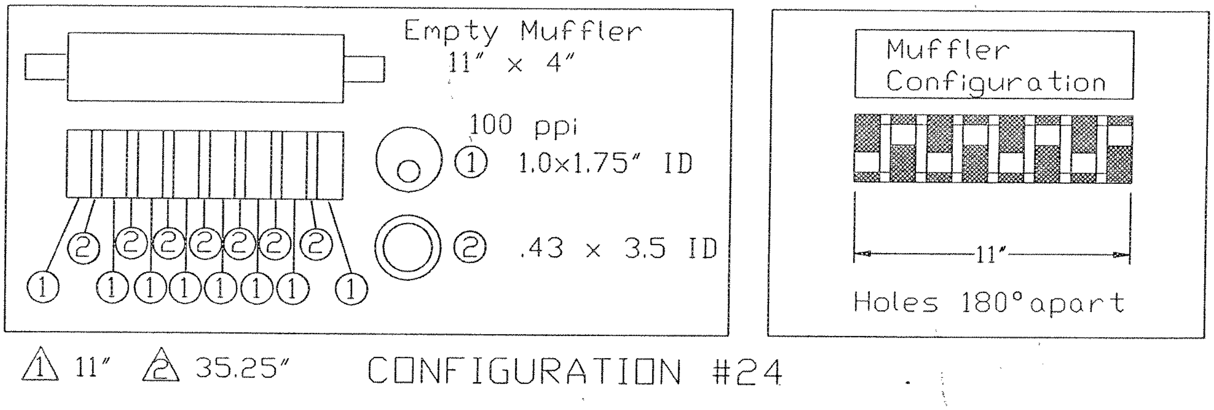
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	104	94	61	61	10	49
60	16667	110	105	98	63	63	7	47
80	12500	110	105	95	62	62	10	48
100	10000	110	106	97	62	61	9	48
120	8333	110	107	100	65	65	7	45
140	7143	110	107	103	67	67	4	43
160	6250	110	103	102	66	65	1	44
180	5556	110	110	101	67	68	9	43
200	5000	110	108	101	69	69	7	41
240	4167	110	105	101	72	73	4	38
280	3571	110	109	104	67	68	5	43
320	3125	110	111	101	62	61	10	48
360	2778	110	118	107	72	73	11	38
400	2500	110	124	115	78	78	9	32
450	2222	110	115	110	70	71	5	40
500	2000	110	110	113	75	76	-3	35
550	1818	110	112	115	79	80	-3	31
600	1667	110	111	110	76	77	1	34

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	110	112	79	78	-2	31
700	1429	110	113	118	84	84	-5	26
750	1333	110	112	113	79	81	-1	31
800	1250	110	118	115	77	80	3	33
850	1176	110	117	113	76	76	4	34
900	1111	110	107	107	70	71	0	40
950	1053	110	101	103	65	65	-2	45
1000	1000	110	103	103	82	79	0	28
1100	909	110	110	107	80	82	3	30
1200	833	110	121	107	86	87	14	24
1300	769	110	117	101	81	82	16	29
1400	714	110	123	109	77	79	14	33
1500	667	110	126	104	62	66	22	48
1600	625	110	118	102	67	66	16	43
1700	588	110	118	107	75	76	11	35
1800	556	110	117	108	77	80	9	33
1900	526	110	102	100	66	69	2	44
2000	500	110	100	97	69	70	3	41
2200	455	110	95	83	59	62	12	51
2400	417	110	101	84	71	74	17	39
2600	385	110	98	75	66	67	23	44
2800	357	110	85	67	58	58	18	52
3000	333	110	103	89	78	81	14	32



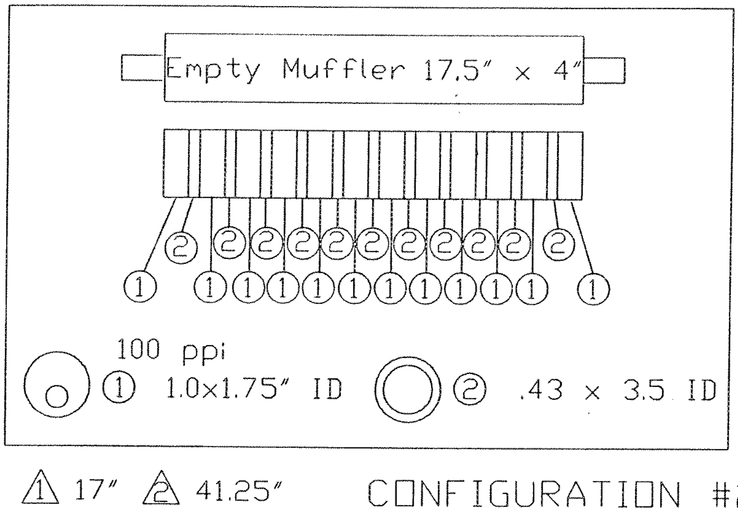
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	104	90	58	58	14	52
60	16667	110	104	92	60	60	12	50
80	12500	110	105	90	59	59	15	51
100	10000	110	105	93	58	58	12	52
120	8333	110	105	96	62	62	9	48
140	7143	110	103	98	63	63	5	47
160	6250	110	103	96	60	60	7	50
180	5556	110	104	96	65	64	8	45
200	5000	110	107	96	63	63	11	47
240	4167	110	107	96	72	72	11	38
280	3571	110	110	98	70	70	12	40
320	3125	110	110	100	63	64	10	47
360	2778	110	112	102	70	67	10	40
400	2500	110	114	104	62	62	10	48
450	2222	110	119	108	61	65	11	49
500	2000	110	116	106	70	70	10	40
550	1818	110	112	106	65	65	6	45
600	1667	110	112	106	75	74	6	35

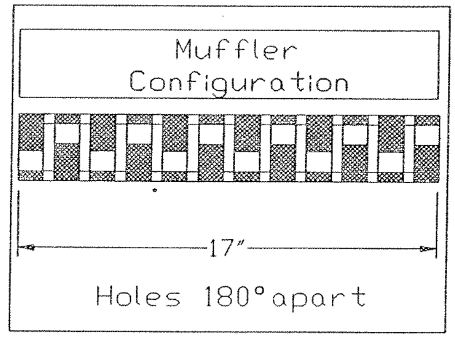
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	106	78	80	6	32
700	1429	110	117	105	77	79	12	33
750	1333	110	113	105	73	73	8	37
800	1250	110	115	106	64	66	9	46
850	1176	110	117	106	69	70	11	41
900	1111	110	113	101	65	66	12	45
950	1053	110	110	98	70	72	12	40
1000	1000	110	106	95	78	78	11	32
1100	909	110	110	97	74	74	13	36
1200	833	110	122	101	77	79	21	33
1300	769	110	122	93	67	70	29	43
1400	714	110	126	105	64	59	21	46
1500	667	110	121	93	58	66	28	52
1600	625	110	112	87	57	63	25	53
1700	588	110	117	92	58	58	25	52
1800	556	110	110	90	61	62	20	49
1900	526	110	111	95	70	70	16	40
2000	500	110	99	83	58	57	16	52
2200	455	110	95	78	66	64	17	44
2400	417	110	97	71	59	58	26	51
2600	385	110	91	58	51	52	33	59
2800	357	110	101	69	62	52	32	48
3000	333	110	75	58	50	50	17	60



FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	103	81	56	56	22	54
60	16667	110	102	81	56	56	21	54
80	12500	110	104	82	57	57	22	53
100	10000	110	104	82	54	54	22	56
120	8333	110	104	84	55	55	20	55
140	7143	110	104	87	59	59	17	51
160	6250	110	105	92	60	60	13	50
180	5556	110	107	95	65	65	12	45
200	5000	110	109	95	64	64	14	46
240	4167	110	106	97	72	72	9	38
280	3571	110	109	100	70	70	9	40
320	3125	110	109	98	65	66	11	45
360	2778	110	113	101	68	58	12	42
400	2500	110	118	107	66	68	11	44
450	2222	110	117	109	62	64	8	48
500	2000	110	115	111	73	74	4	37
550	1818	110	112	111	68	67	1	42
600	1667	110	111	108	72	74	3	38

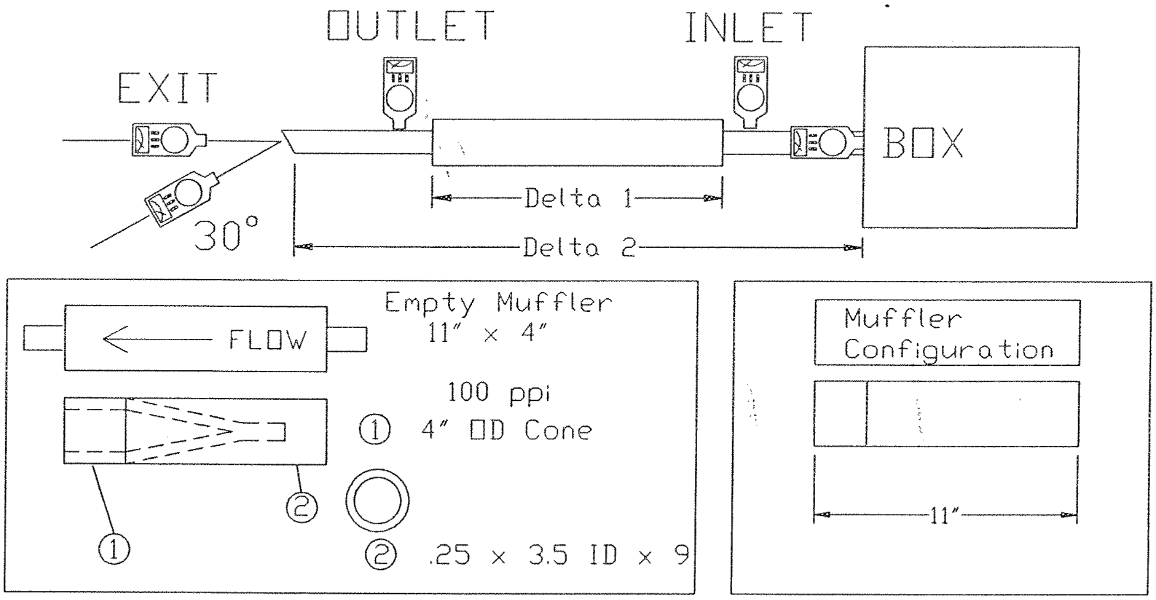
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	108	81	82	3	29
700	1429	110	118	106	77	78	12	33
750	1333	110	113	106	77	75	7	33
800	1250	110	117	107	66	68	10	44
850	1176	110	118	110	73	74	8	37
900	1111	110	113	106	64	64	7	46
950	1053	110	113	106	75	78	7	35
1000	1000	110	111	105	72	68	6	38
1100	909	110	110	103	75	63	7	35
1200	833	110	118	104	82	84	14	28
1300	769	110	121	99	77	77	22	33
1400	714	110	126	113	70	75	13	40
1500	667	110	121	101	66	68	20	44
1600	625	110	111	95	69	65	16	41
1700	588	110	113	98	73	72	15	37
1800	556	110	111	101	72	74	10	38
1900	526	110	112	102	77	77	10	33
2000	500	110	102	88	64	66	14	46
2200	455	110	100	86	66	64	14	44
2400	417	110	95	80	64	67	15	46
2600	385	110	90	62	64	65	28	46
2800	357	110	97	59	50	50	38	60
3000	333	110	88	50	50	50	38	60





FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30°	Δ1	Δ2
40	25000	110	107	90	58	58	17	52
60	16667	110	106	93	61	61	13	49
80	12500	110	107	91	59	59	16	51
100	10000	110	108	94	60	61	14	50
120	8333	110	106	97	62	63	9	48
140	7143	110	102	97	61	62	5	49
160	6250	110	103	95	58	59	8	52
180	5556	110	105	95	65	65	10	45
200	5000	110	108	96	64	65	12	46
240	4167	110	108	96	73	73	12	37
280	3571	110	110	98	70	70	12	40
320	3125	110	108	99	64	64	9	46
360	2778	110	110	100	73	72	10	37
400	2500	110	115	104	68	68	11	42
450	2222	110	118	107	64	67	11	46
500	2000	110	116	107	67	69	9	43
550	1818	110	115	107	70	69	8	40
600	1667	110	112	105	80	79	7	30

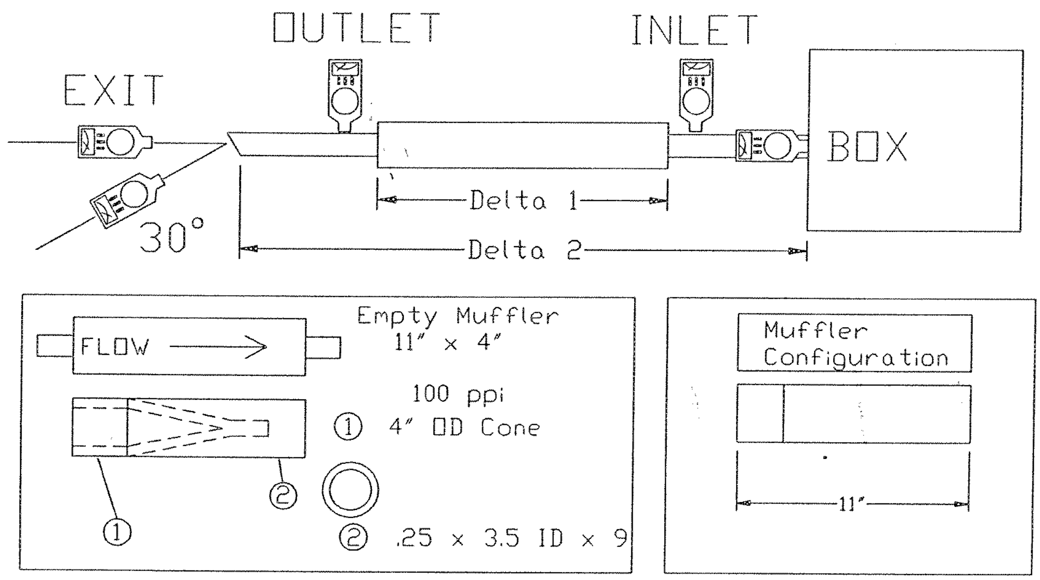
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	112	105	73	73	7	37
700	1429	110	119	102	77	78	17	33
750	1333	110	115	102	56	53	13	54
800	1250	110	117	103	72	71	14	38
850	1176	110	118	104	70	70	14	40
900	1111	110	117	102	63	62	15	47
950	1053	110	115	100	65	66	15	45
1000	1000	110	111	97	75	77	14	35
1100	909	110	110	97	72	74	13	38
1200	833	110	119	97	78	78	22	32
1300	769	110	121	91	71	72	30	39
1400	714	110	126	105	70	66	21	40
1500	667	110	122	91	55	60	31	55
1600	625	110	112	86	63	70	26	47
1700	588	110	113	88	63	66	25	47
1800	556	110	113	92	65	58	21	45
1900	526	110	111	89	68	64	22	42
2000	500	110	101	77	55	50	24	55
2200	455	110	100	72	50	50	28	60
2400	417	110	92	63	50	57	29	60
2600	385	110	94	56	50	50	38	60
2800	357	110	93	62	52	50	31	58
3000	333	110	88	61	50	50	27	60



CONFIGURATION #26

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
40	25000	110	103	89	59	60	14	51
60	16667	110	104	91	59	60	13	51
80	12500	110	104	90	60	61	14	50
100	10000	110	105	91	59	60	14	51
120	8333	110	105	94	60	61	11	50
140	7143	110	108	98	65	65	10	45
160	6250	110	108	101	70	69	7	40
180	5556	110	108	105	68	72	3	42
200	5000	110	109	103	69	69	6	41
240	4167	110	105	101	72	73	4	38
280	3571	110	111	103	73	72	8	37
320	3125	110	109	100	66	67	9	44
360	2778	110	113	103	68	66	10	42
400	2500	110	121	112	70	72	9	40
450	2222	110	119	113	72	72	6	38
500	2000	110	112	114	77	78	-2	33
550	1818	110	117	118	78	79	-1	32
600	1667	110	113	112	75	77	1	35

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	0	0
650	1538	110	111	112	83	84	-1	27
700	1429	110	115	115	81	83	0	29
750	1333	110	112	110	76	77	2	34
800	1250	110	115	108	68	70	7	42
850	1176	110	123	114	76	76	9	34
900	1111	110	121	112	74	75	9	36
950	1053	110	113	106	71	71	7	39
1000	1000	110	105	103	77	78	2	33
1100	909	110	114	110	86	86	4	24
1200	833	110	112	110	87	87	2	23
1300	769	110	111	102	84	84	9	26
1400	714	110	126	115	81	83	11	29
1500	667	110	122	105	67	68	17	43
1600	625	110	112	97	65	61	15	45
1700	588	110	114	105	75	76	9	35
1800	556	110	115	111	80	82	4	30
1900	526	110	114	112	83	85	2	27
2000	500	110	105	97	68	68	8	42
2200	455	110	103	98	73	76	5	37
2400	417	110	93	94	79	81	-1	31
2600	385	110	92	79	71	73	13	39
2800	357	110	98	82	74	75	16	36
3000	333	110	88	79	70	69	9	40



CONFIGURATION #27

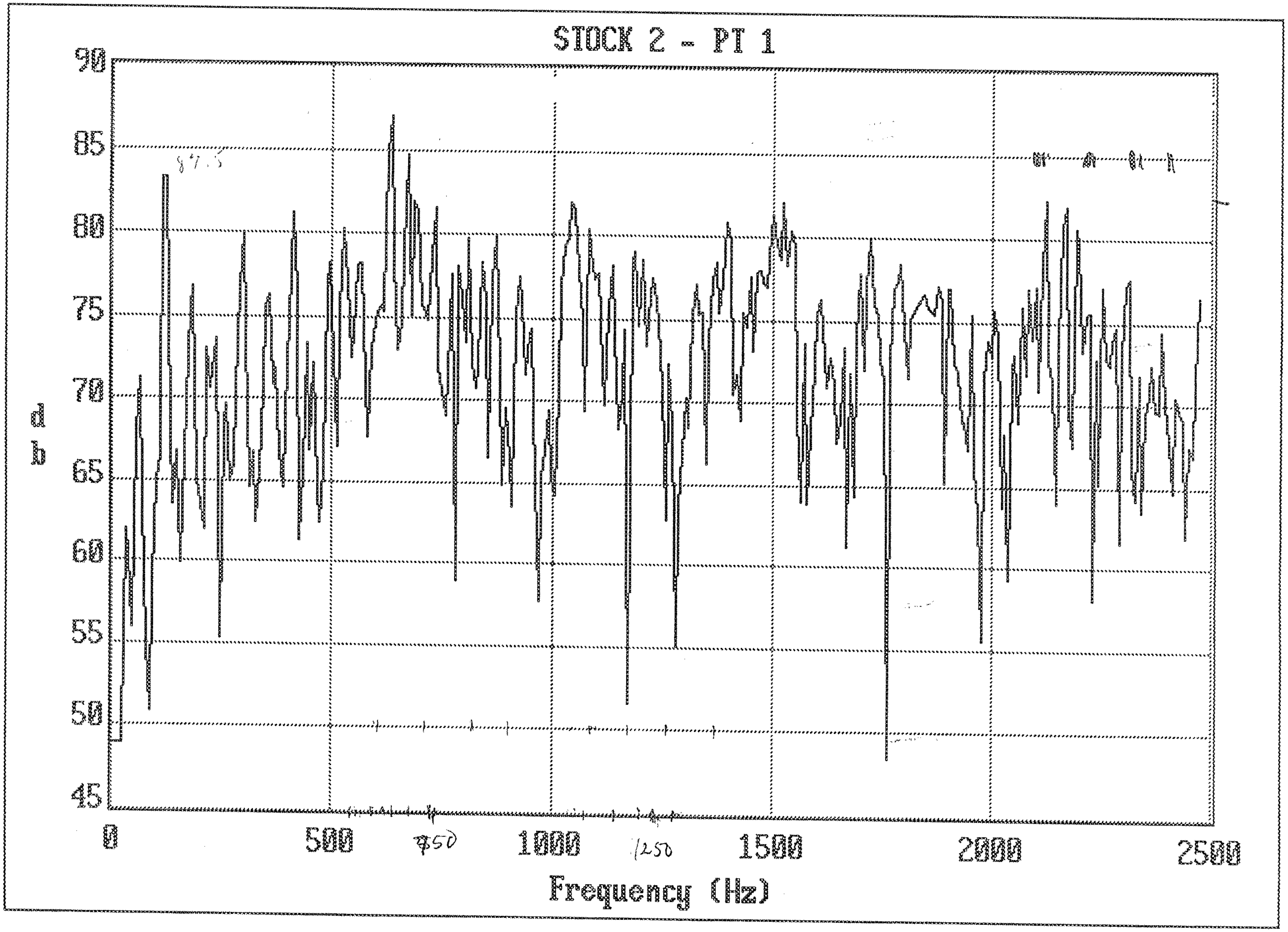
FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30⁰	Δ1	Δ2
40	25000	110	104	88	58	58	16	52
60	16667	110	103	90	58	58	13	52
80	12500	110	105	90	59	60	15	51
100	10000	110	105	70	58	59	35	52
120	8333	110	105	93	59	59	12	51
140	7143	110	107	97	63	63	10	47
160	6250	110	108	100	68	68	8	42
180	5556	110	108	103	69	70	5	41
200	5000	110	106	102	68	68	4	42
240	4167	110	105	101	72	72	4	38
280	3571	110	111	103	72	72	8	38
320	3125	110	110	99	66	66	11	44
360	2778	110	114	103	68	69	11	42
400	2500	110	123	112	72	75	11	38
450	2222	110	115	110	65	66	5	45
500	2000	110	112	109	70	71	3	40
550	1818	110	113	115	79	81	-2	31
600	1667	110	113	112	72	71	1	38

FREQUENCY	COUNT	BOX	INLET	OUTLET	EXIT	30^0	Δ1	Δ2
650	1538	110	111	110	52	83	1	58
700	1429	110	112	117	71	73	-5	39
750	1333	110	113	112	77	78	1	33
800	1250	110	115	110	70	72	5	40
850	1176	110	123	117	74	75	6	36
900	1111	110	117	109	69	71	8	41
950	1053	110	108	103	71	76	5	39
1000	1000	110	98	99	73	72	-1	37
1100	909	110	112	106	80	80	6	30
1200	833	110	112	107	84	84	5	26
1300	769	110	120	101	87	87	19	23
1400	714	110	121	107	82	82	14	28
1500	667	110	126	110	76	75	16	34
1600	625	110	116	98	60	72	18	50
1700	588	110	120	109	71	72	11	39
1800	556	110	116	109	78	79	7	32
1900	526	110	116	111	78	79	5	32
2000	500	110	102	103	73	73	-1	37
2200	455	110	97	99	70	73	-2	40
2400	417	110	93	86	68	69	7	42
2600	385	110	79	85	74	77	-6	36
2800	357	110	101	85	77	77	16	33
3000	333	110	87	79	68	69	8	42

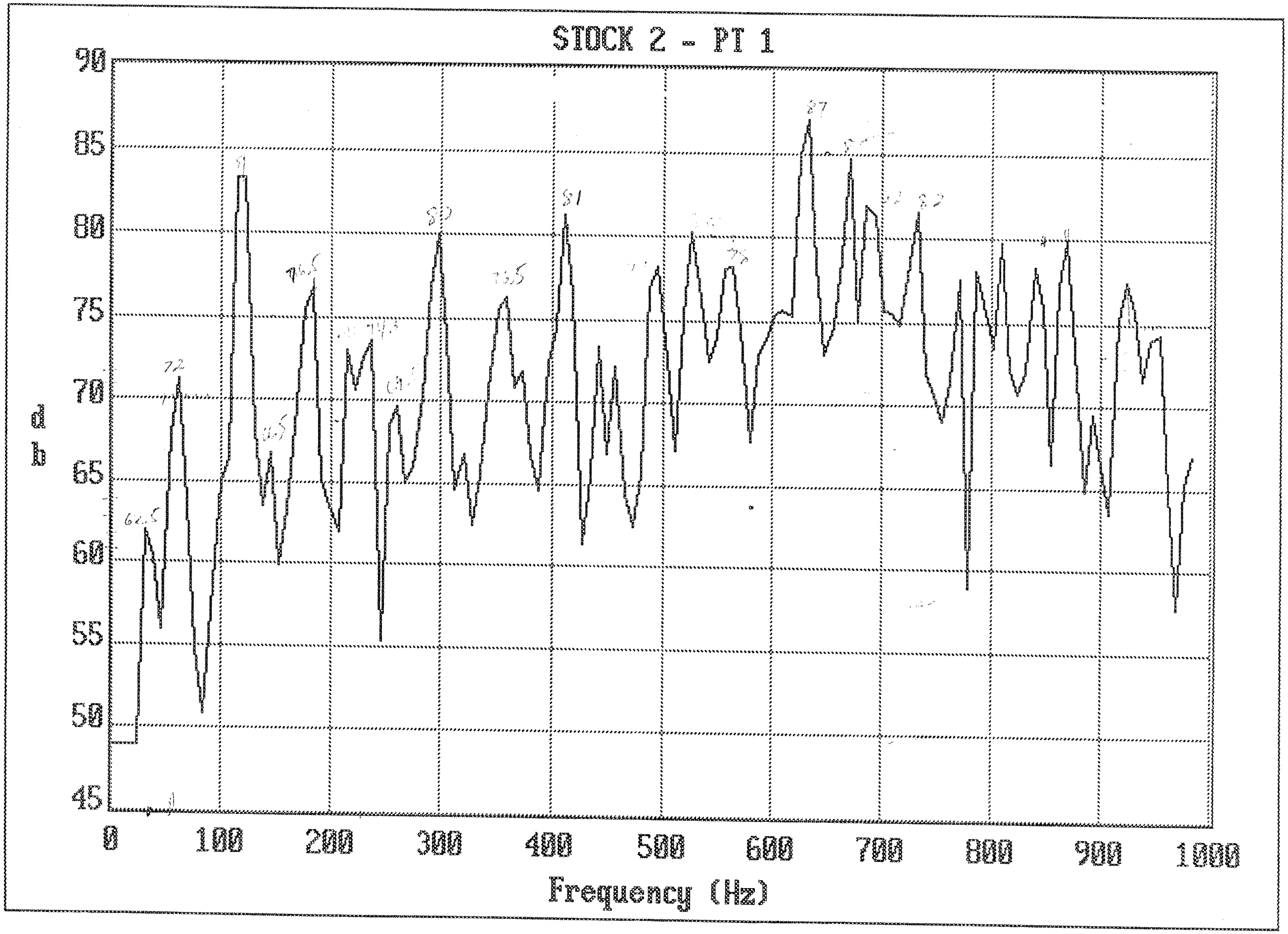
APPENDIX B.

Sound Pressure Level Spectra Recorded from Prototype Mufflers
During Ground Testing

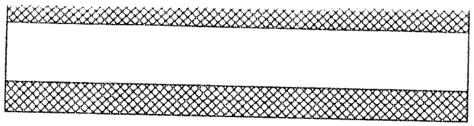
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
AFTERNOON YO-3A STOCK TAILPIPE BASELINE



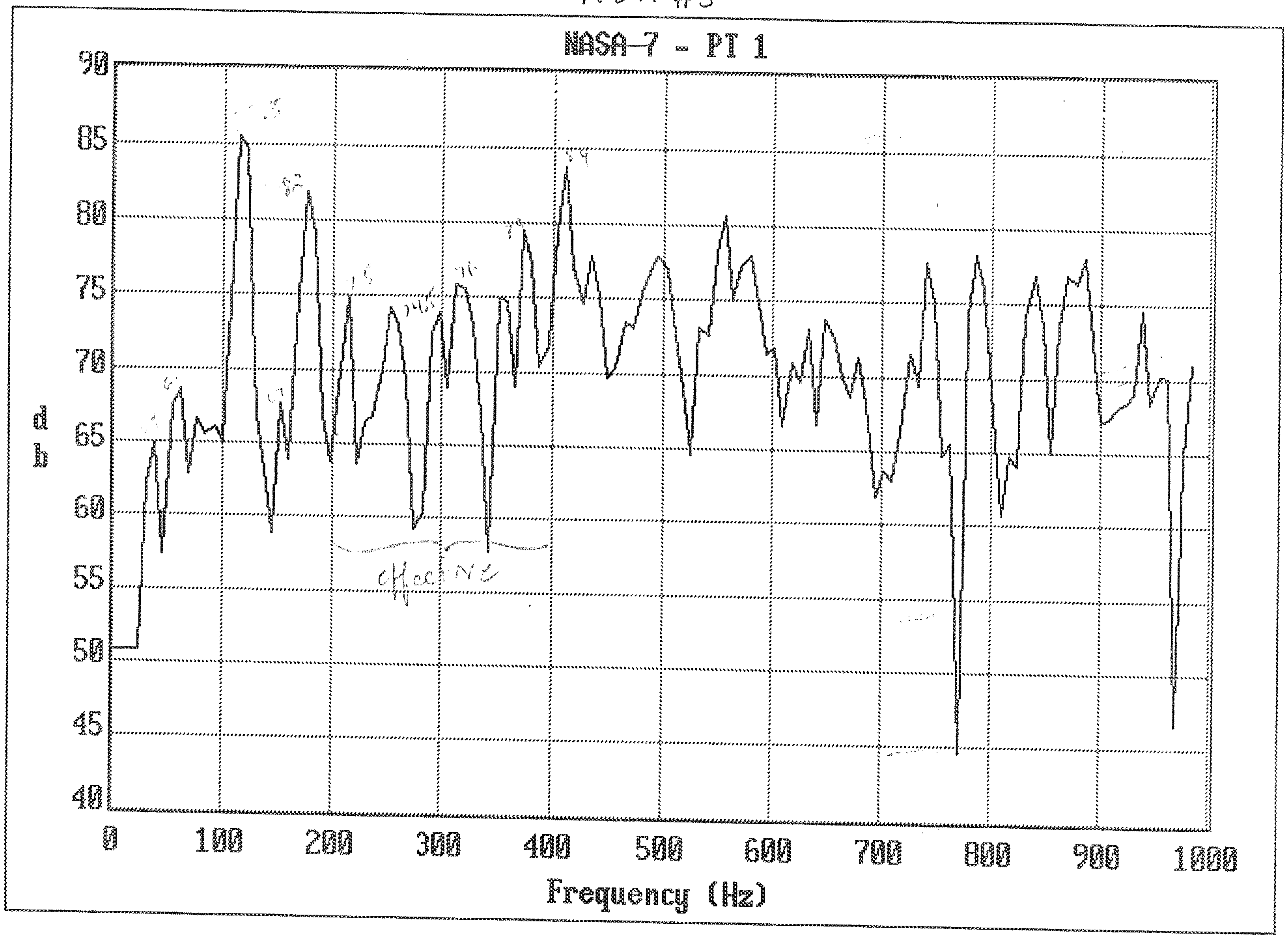
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
AFTERNOON YO-3A STOCK TAILPIPE BASELINE



ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #7

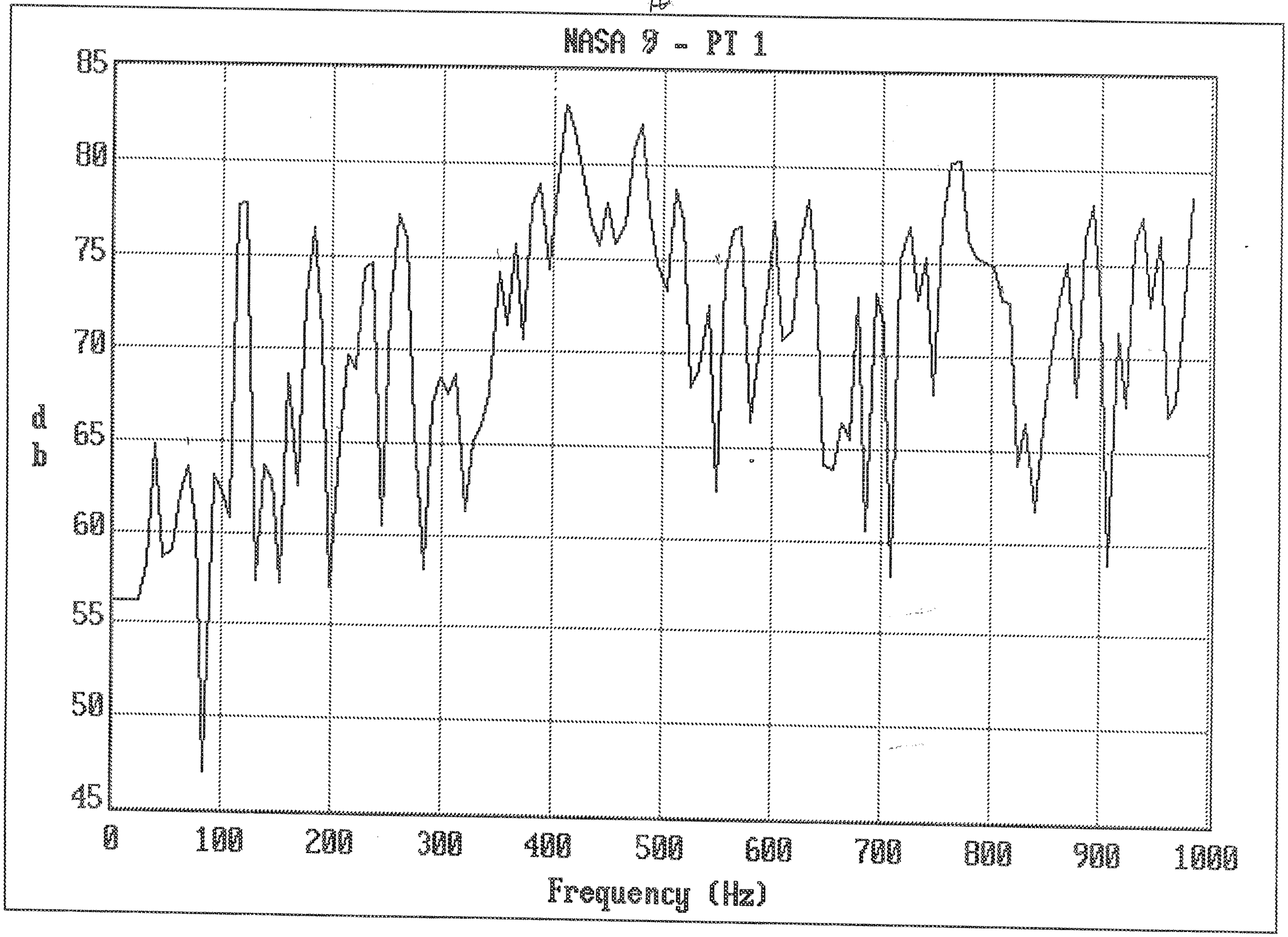


Prod. #5



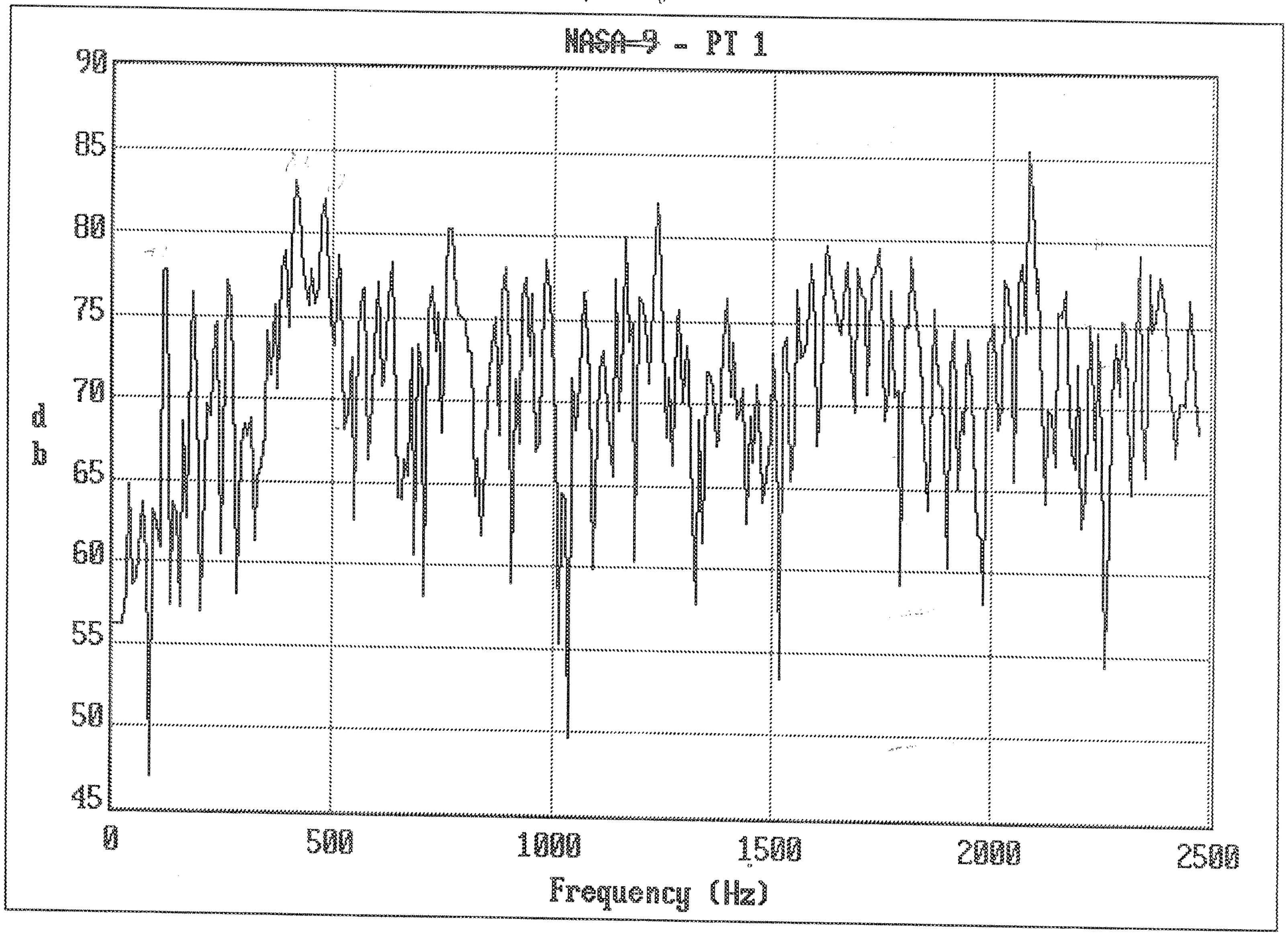
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #~~9~~ 10

Prot. #6 10



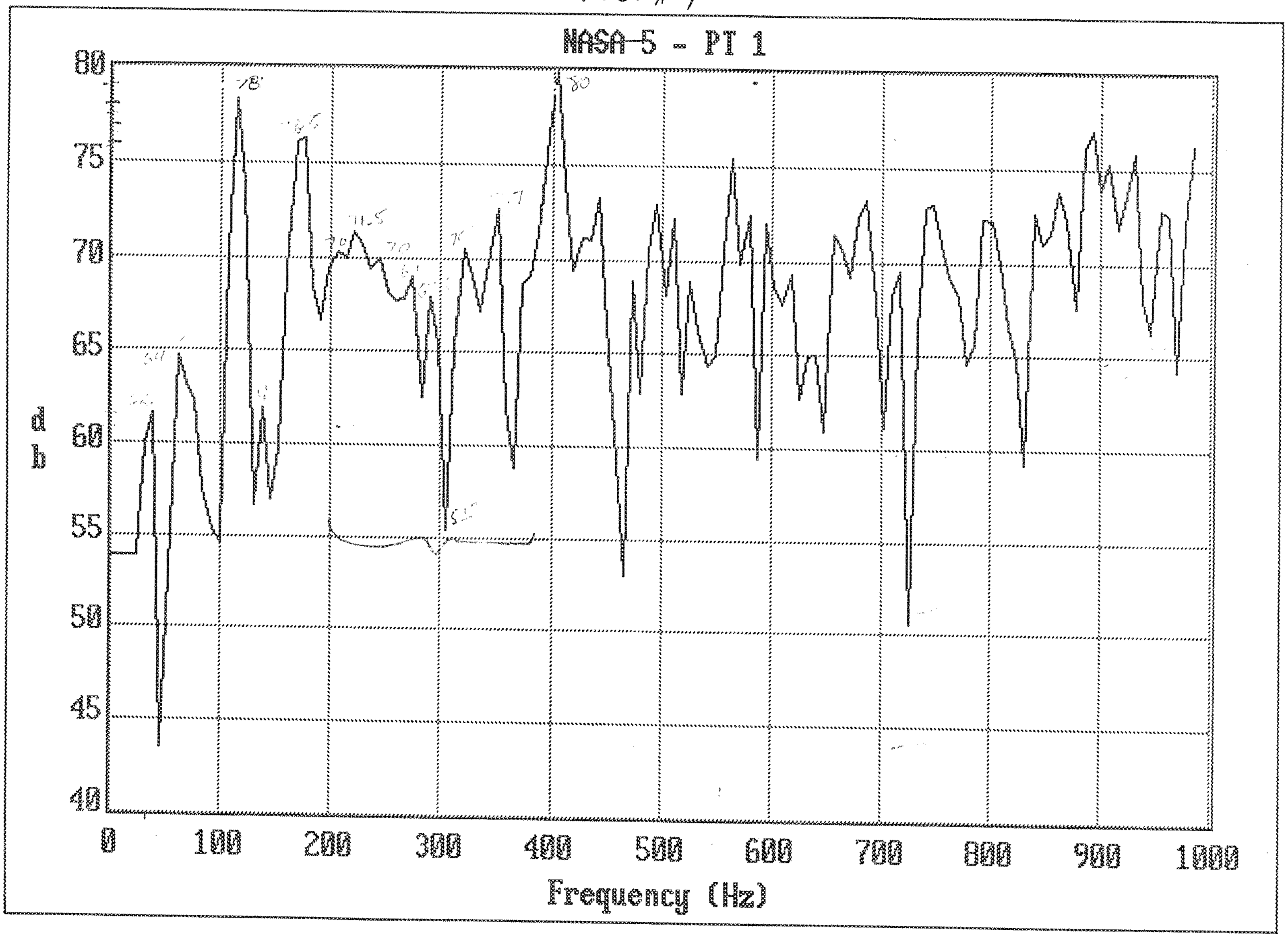
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #9

Pror #6



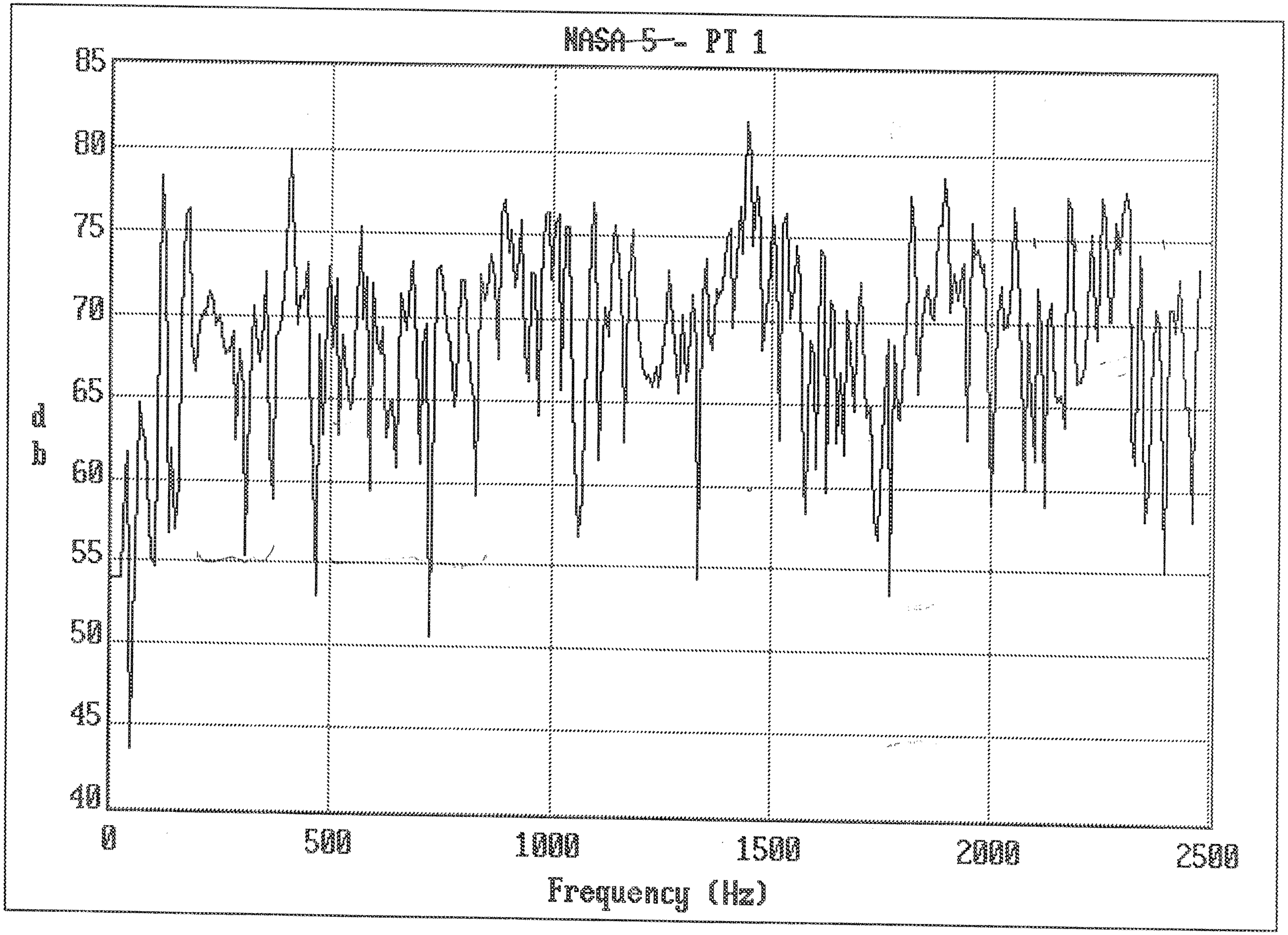
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #5

Prot #7

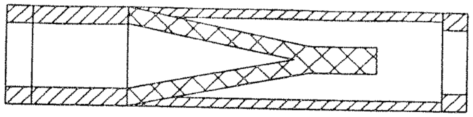


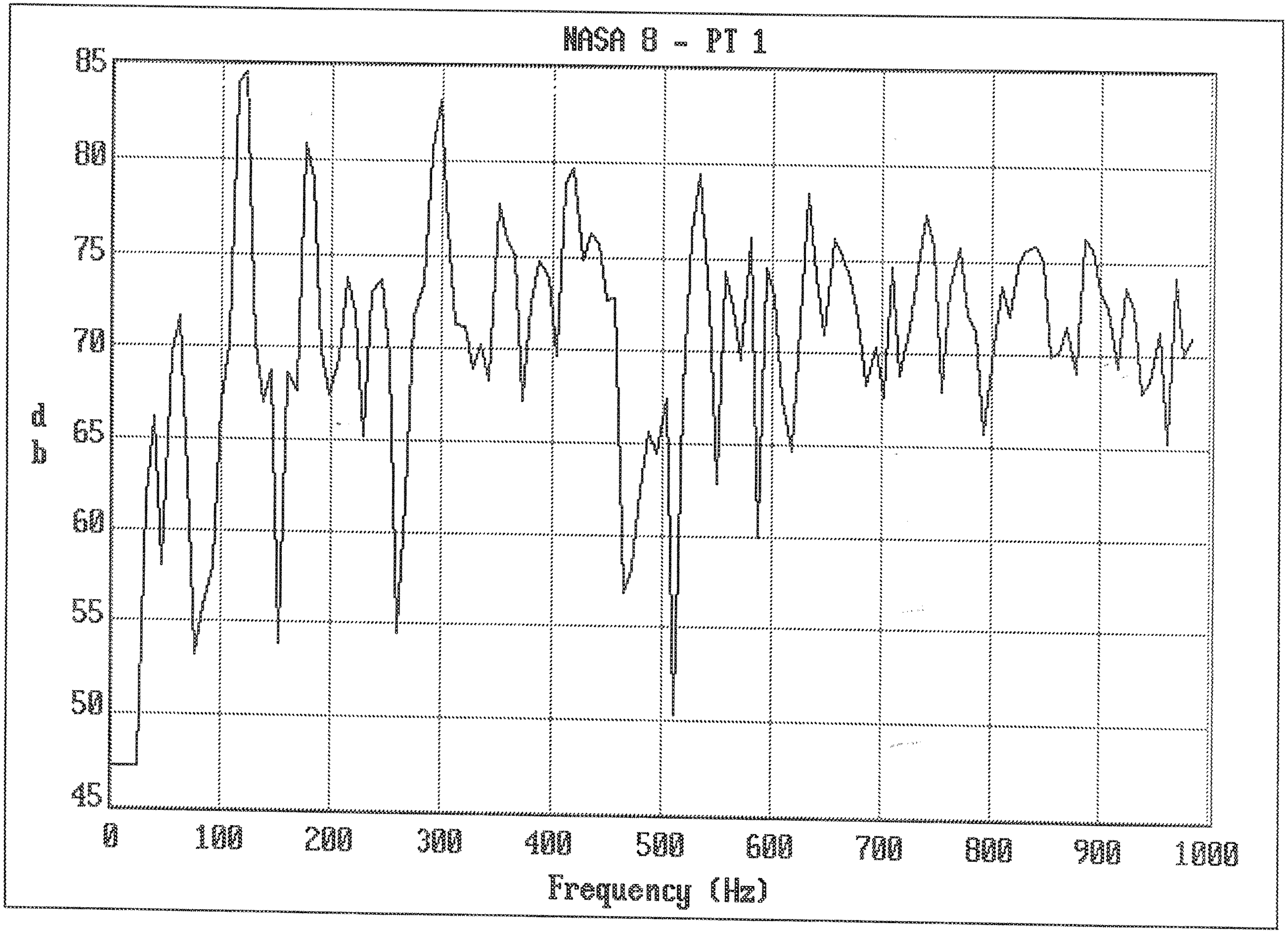
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #5

Prot. #7

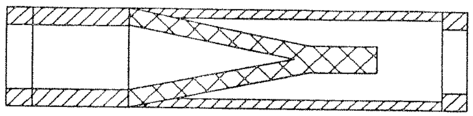


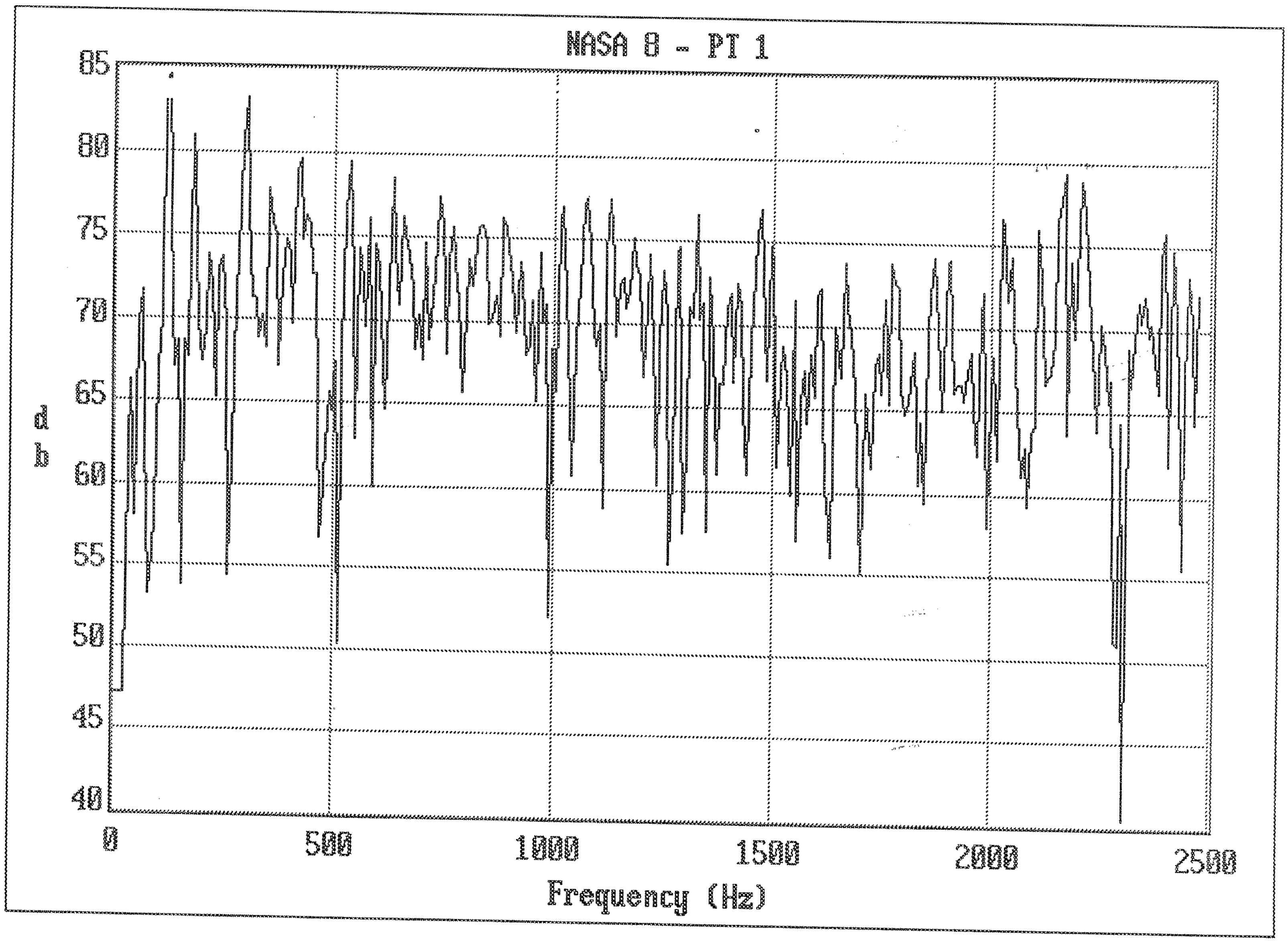
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #8





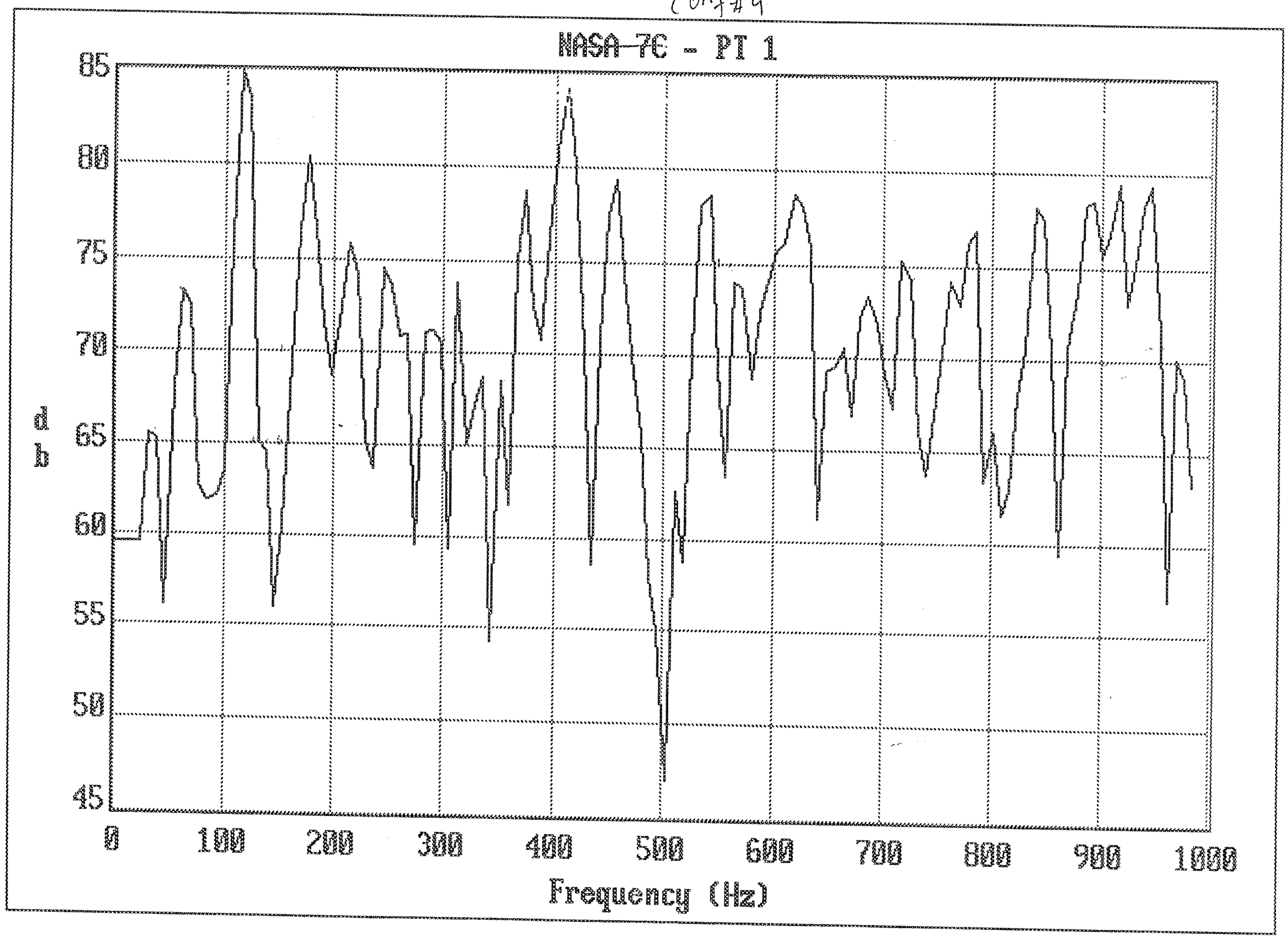
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #8

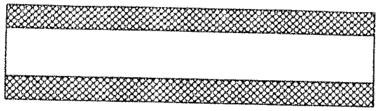




ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #7 WITH .002 SHIM AND FIBER FRAX PAPER

conf#9

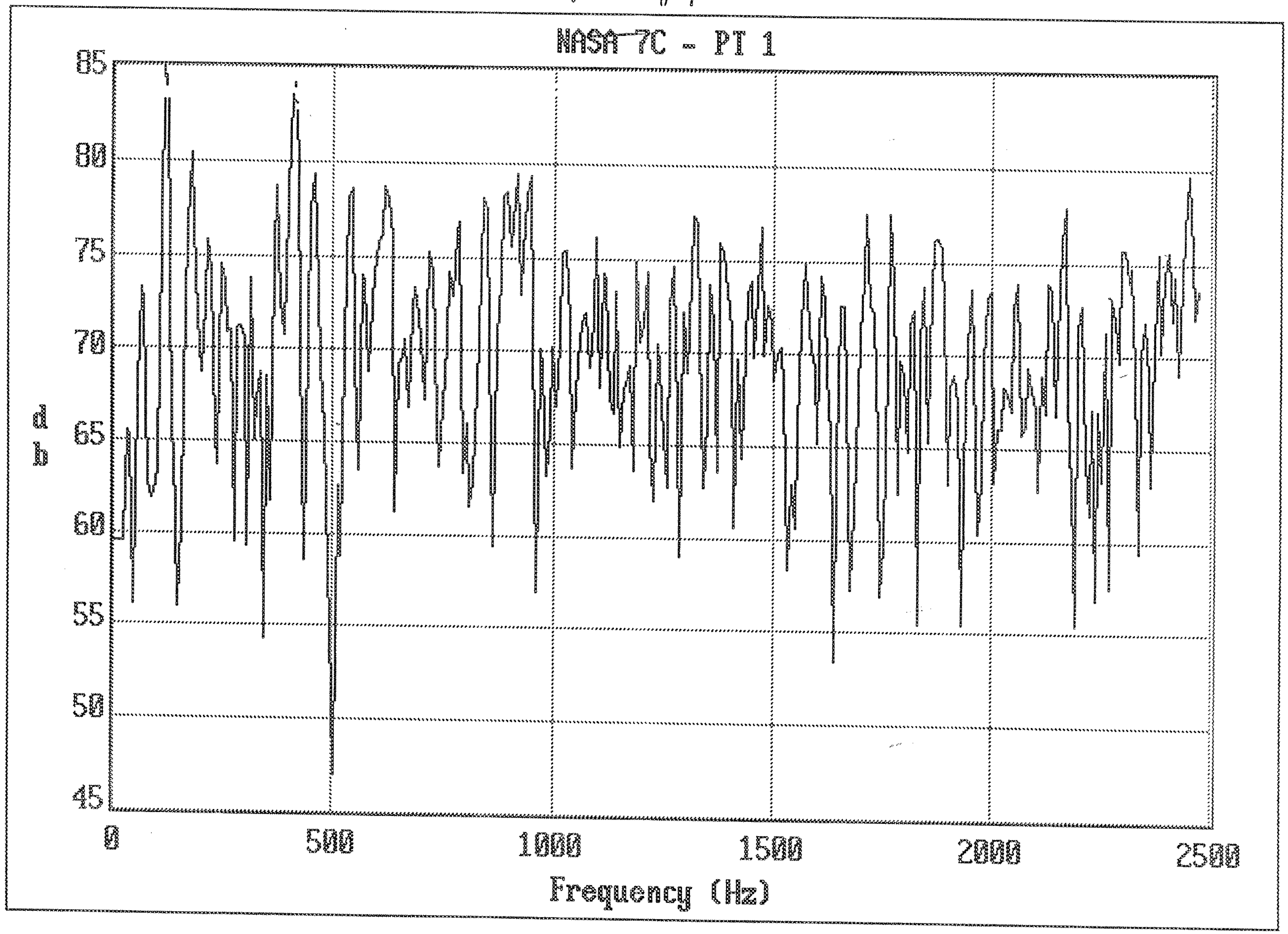


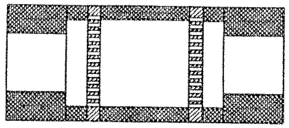


#9

ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #7 WITH .002 SHIM AND FIBER FRAX PAPER

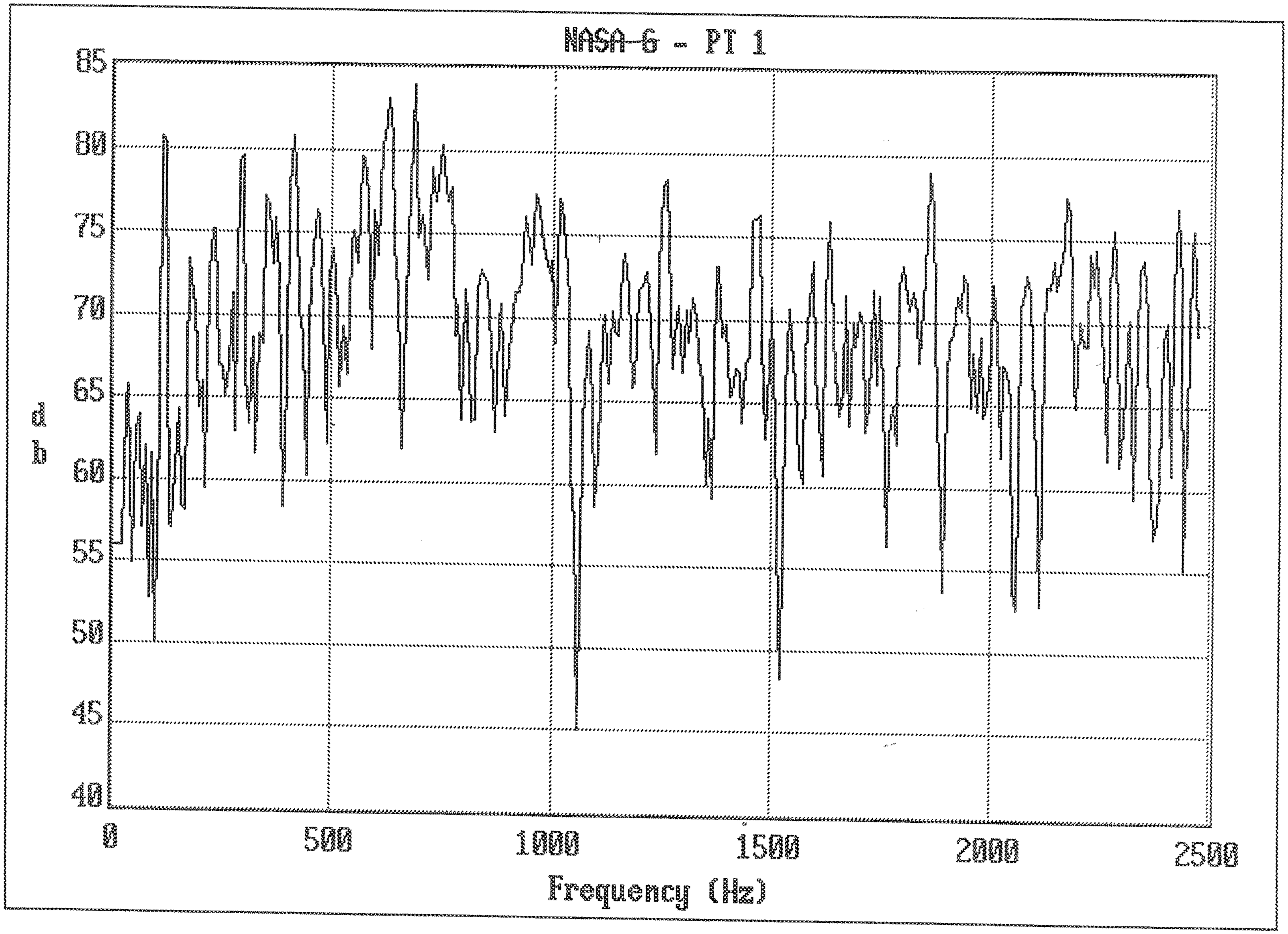
Prot. #9

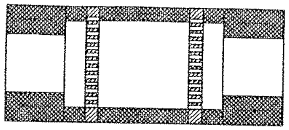




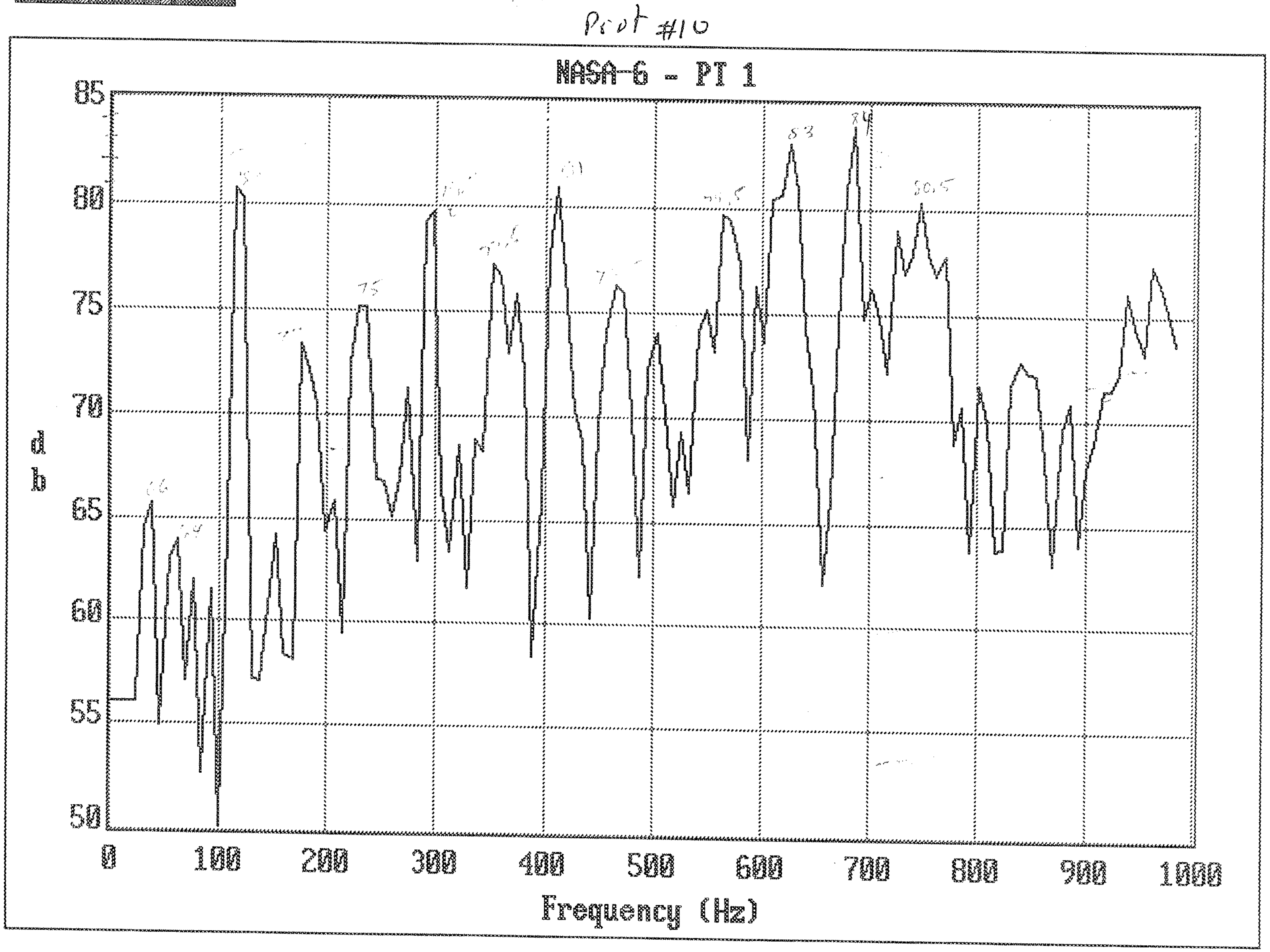
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #6

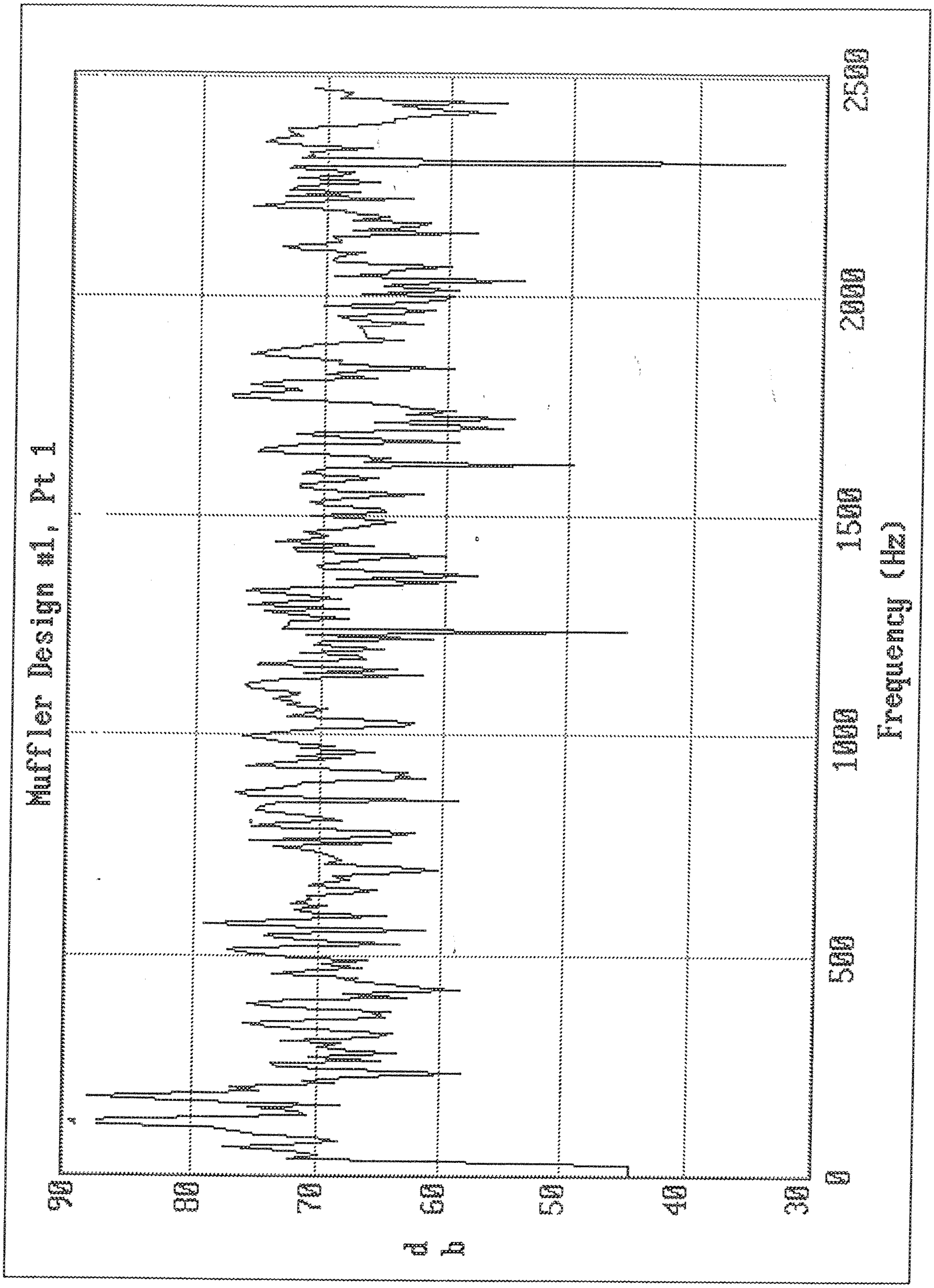
Prot. #10

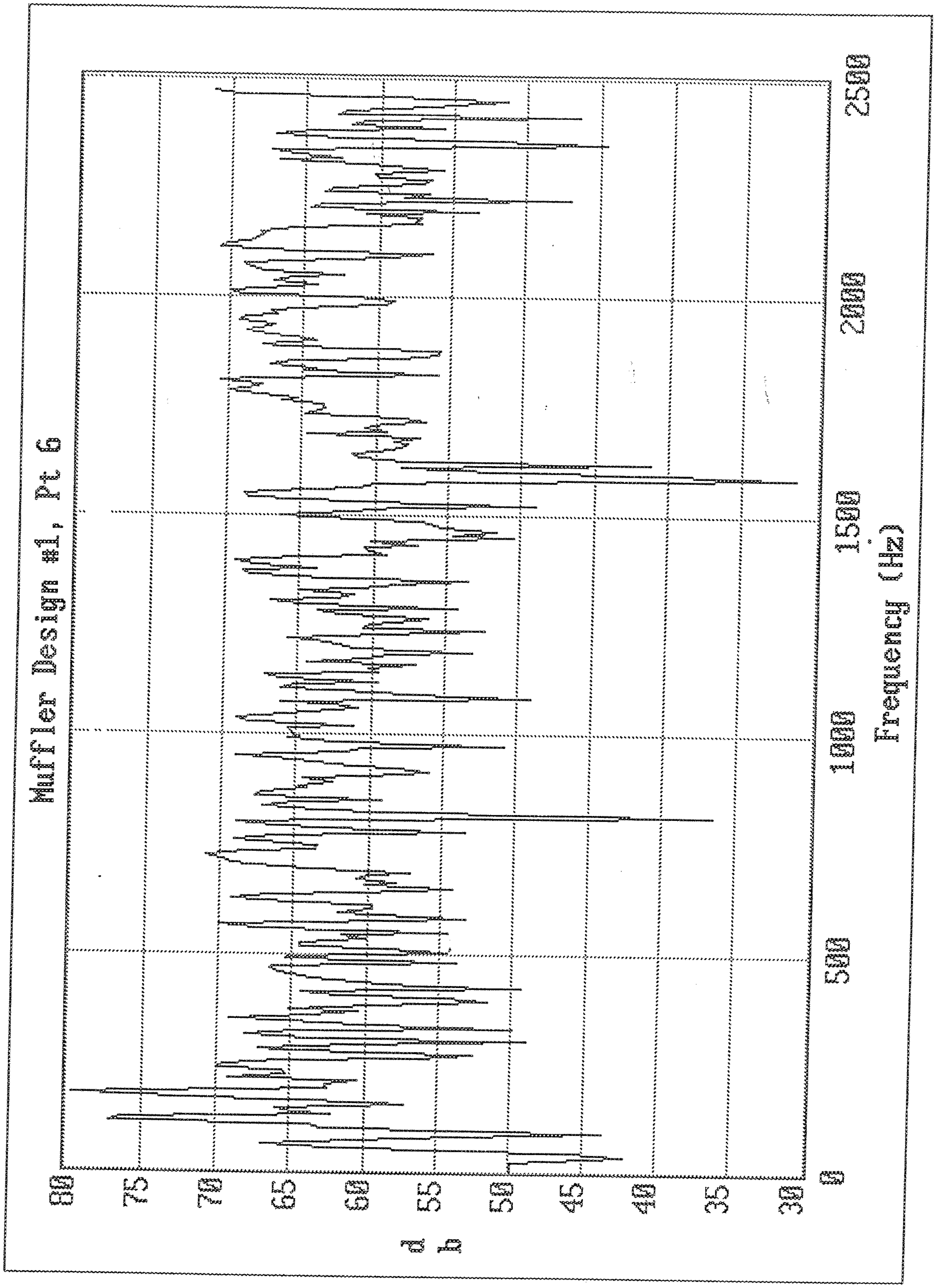


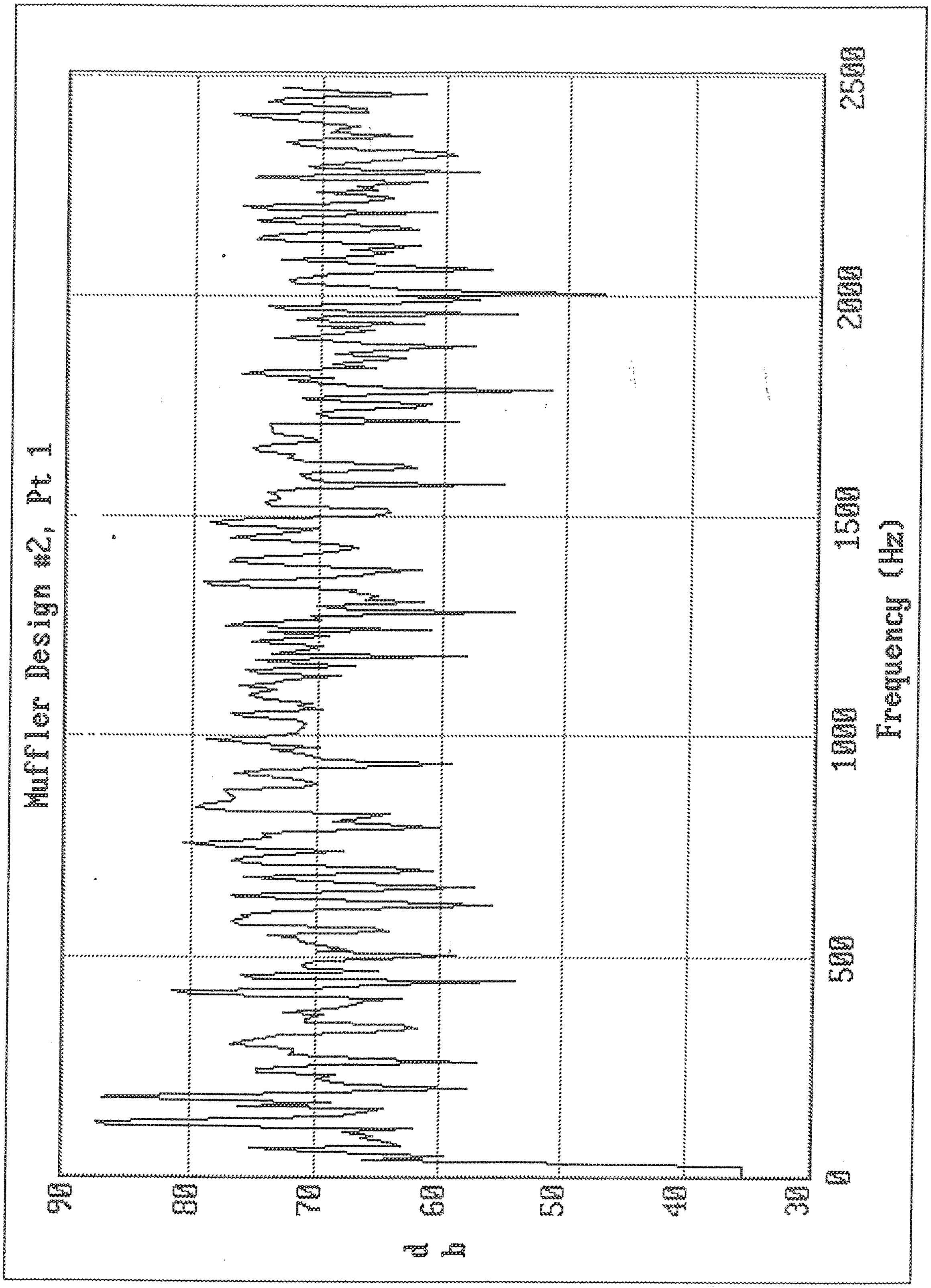


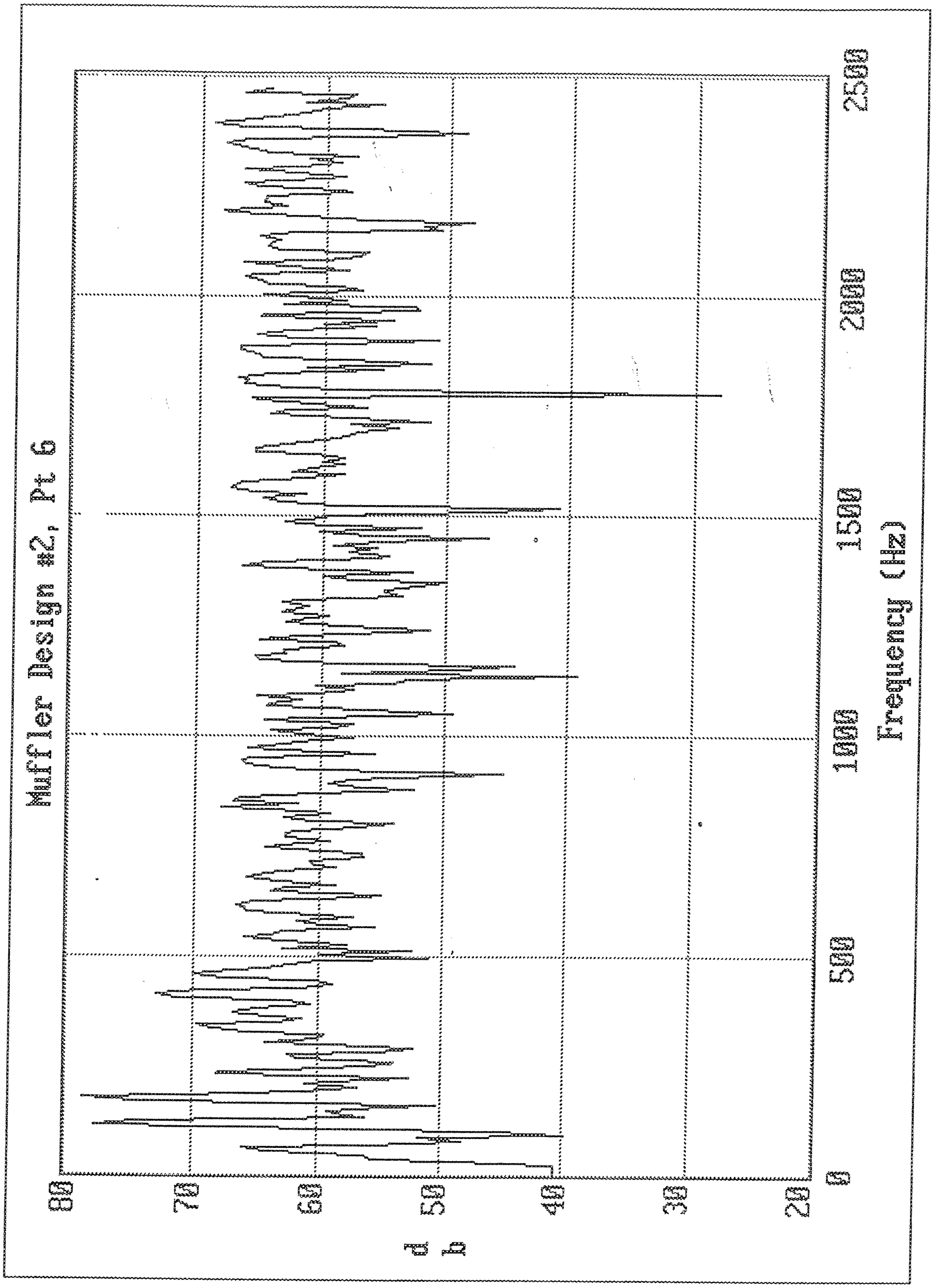
ULTRAMET MUFFLER TESTING ON NASA YO-3A
NASA DRYDEN TEST FACILITY, AUGUST 14, 1997
NASA MUFFLER CONFIGURATION #6

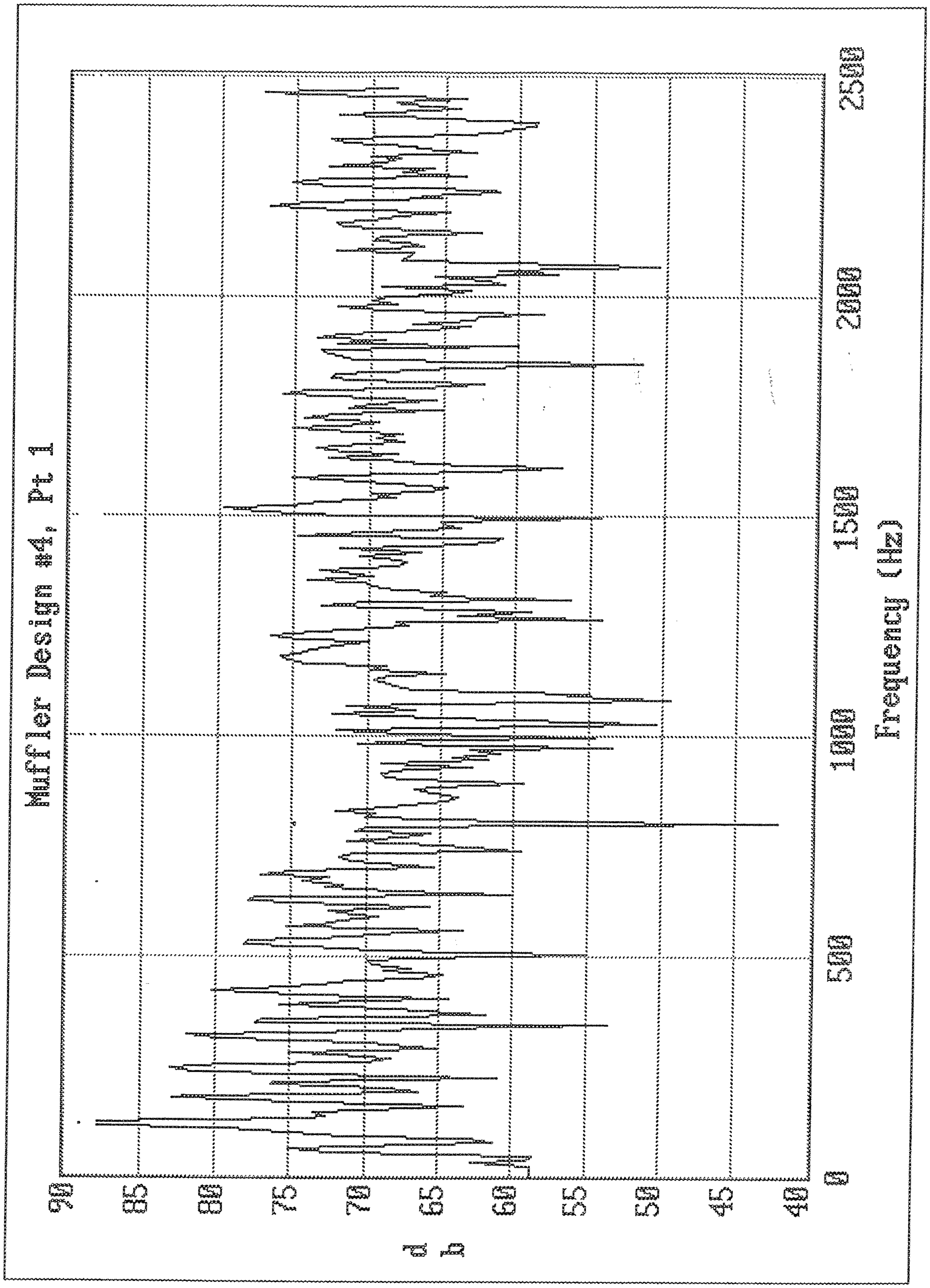


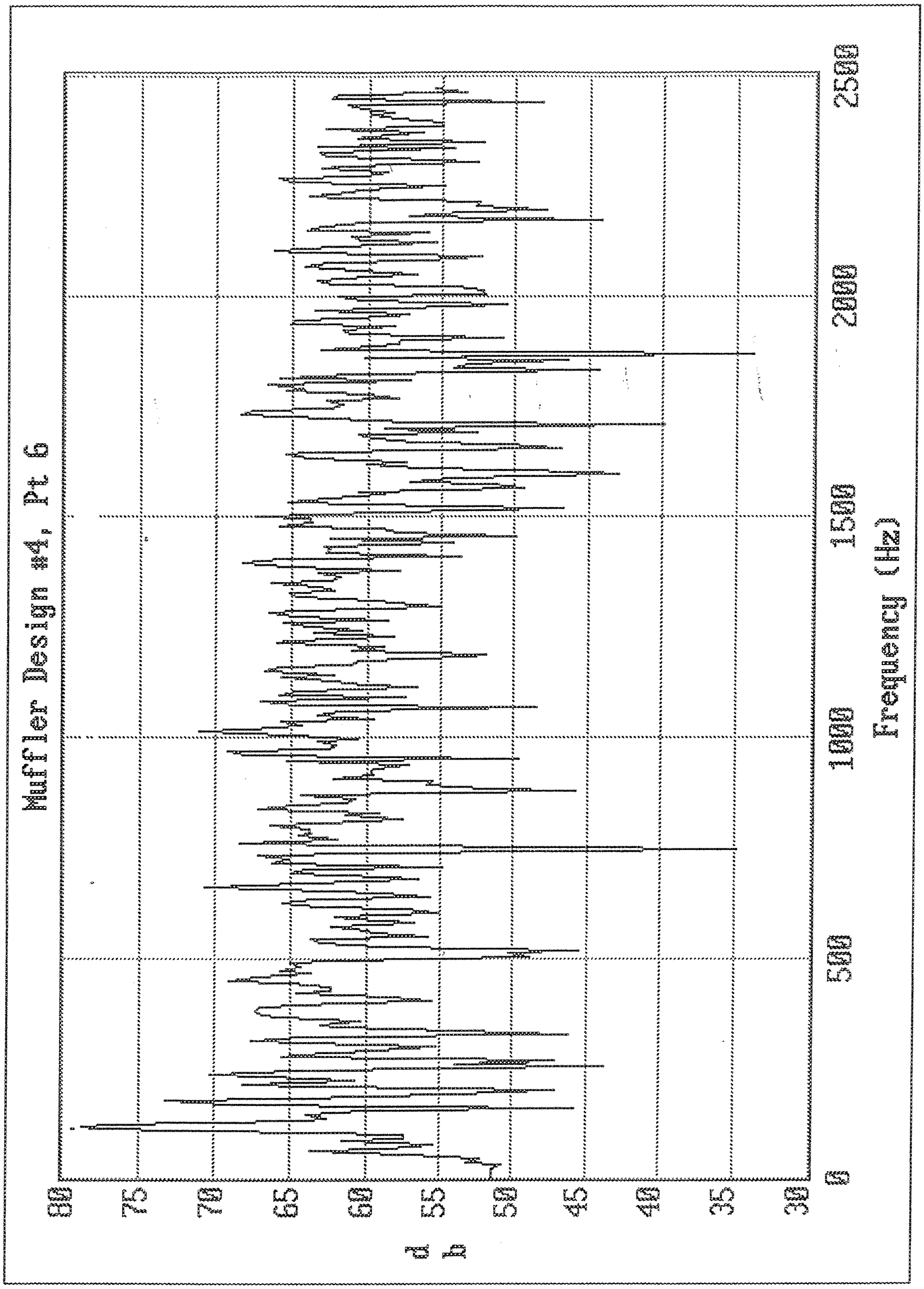

Muffler Design #1, Pt 1
d b
90
80
70
60
50
40
30
0
500
1000
1500
2000
2500
Frequency (Hz)


Muffler Design #1, Pt 6
db
80
75
70
65
60
55
50
45
40
35
30
0
500
1000
1500
2000
2500
Frequency (Hz)


Muffler Design #2, Pt 1
db
90
80
70
60
50
40
30
0
500
1000
1500
2000
2500
Frequency (Hz)


Muffler Design #2, Pt 6
db
80
70
60
50
40
30
20
0
500
1000
1500
2000
2500
Frequency (Hz)

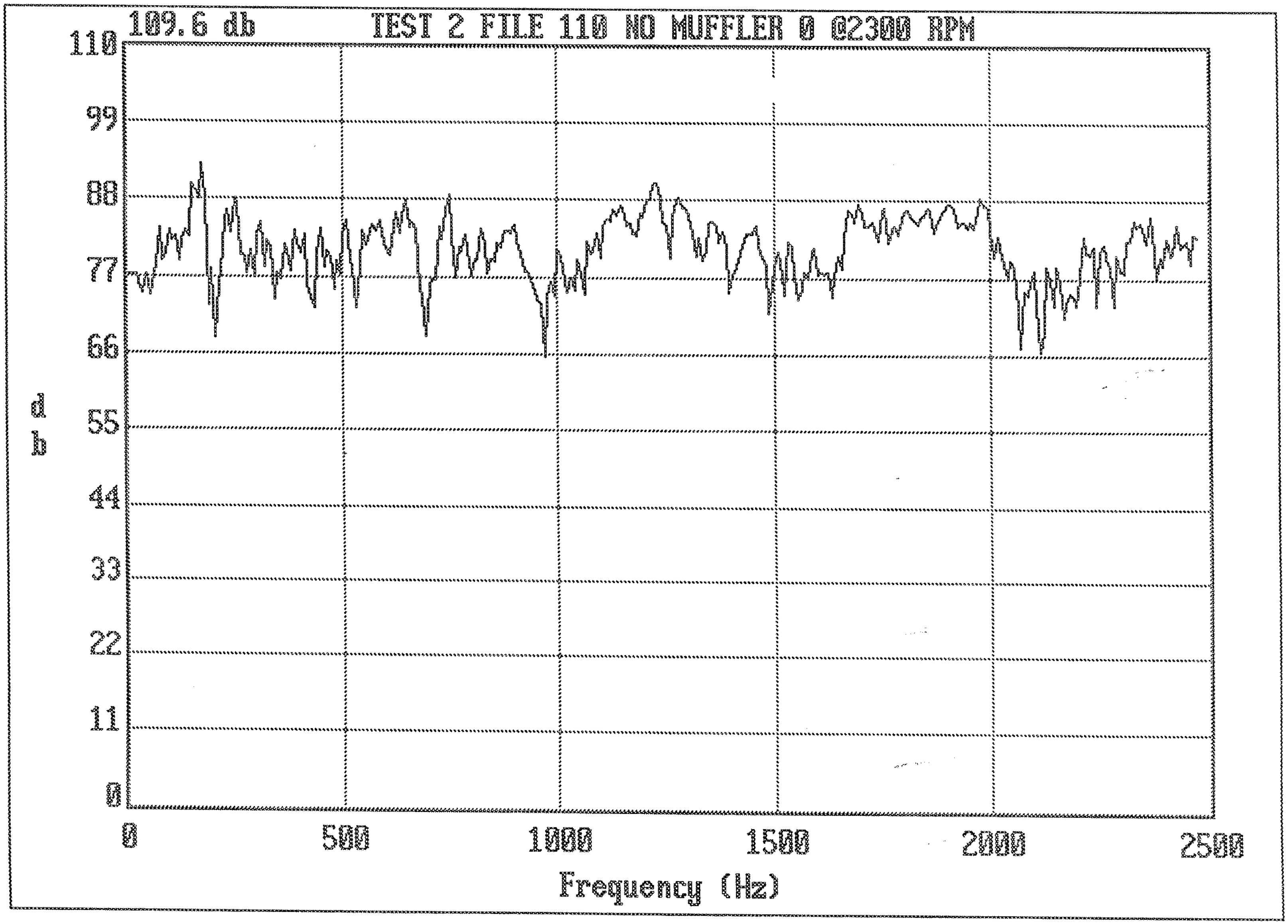

Muffler Design #4, Pt 1
db
90
85
80
75
70
65
60
55
50
45
40
0
500
1000
1500
2000
2500
Frequency (Hz)


Muffler Design #4, Pt 6
d
b
80
75
70
65
60
55
50
45
40
35
30
0
500
1000
1500
2000
2500
Frequency (Hz)

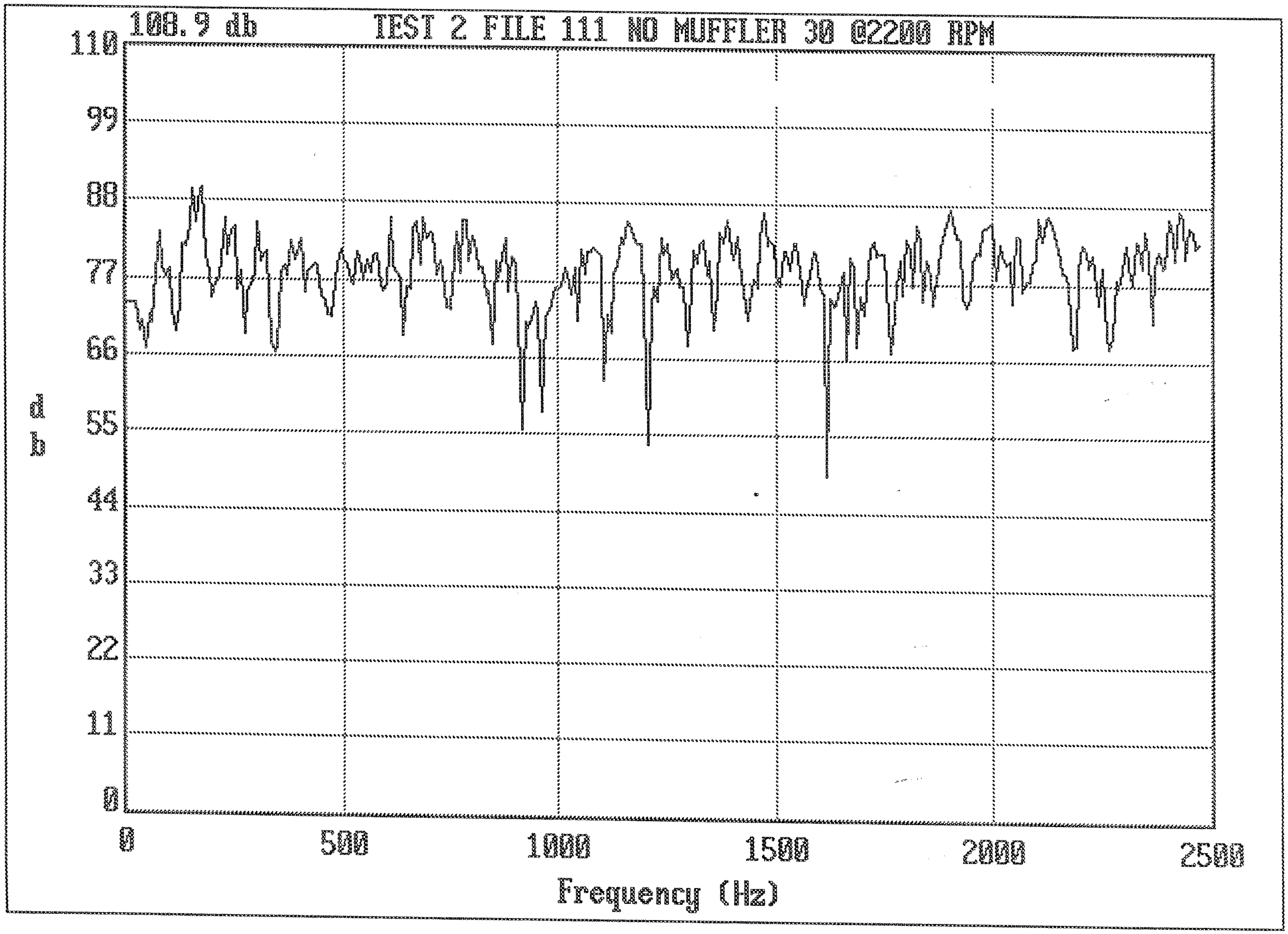
APPENDIX C.

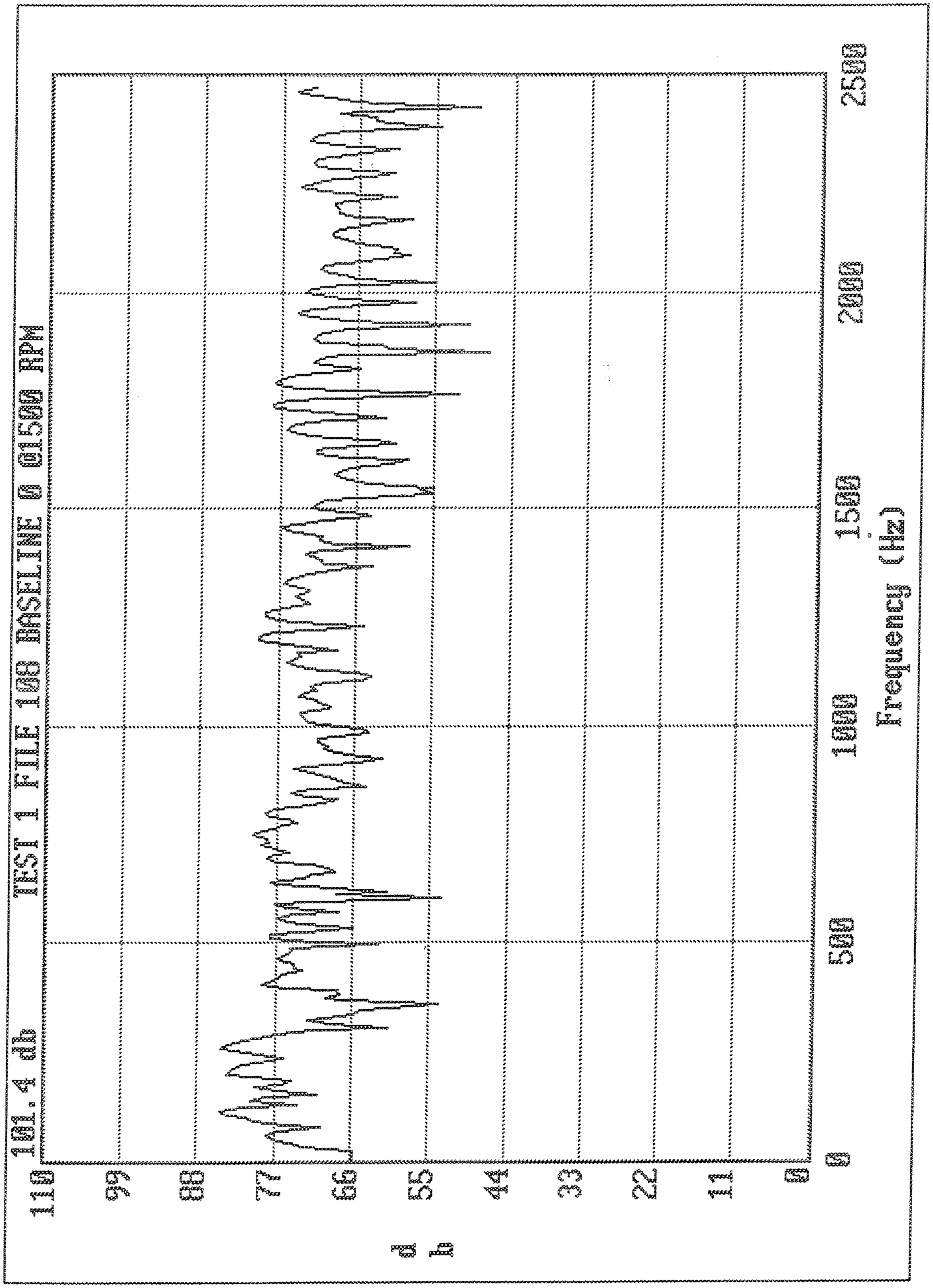
Sound Pressure Level Spectra Recorded from Prototype Mufflers
During Dynamometer Testing

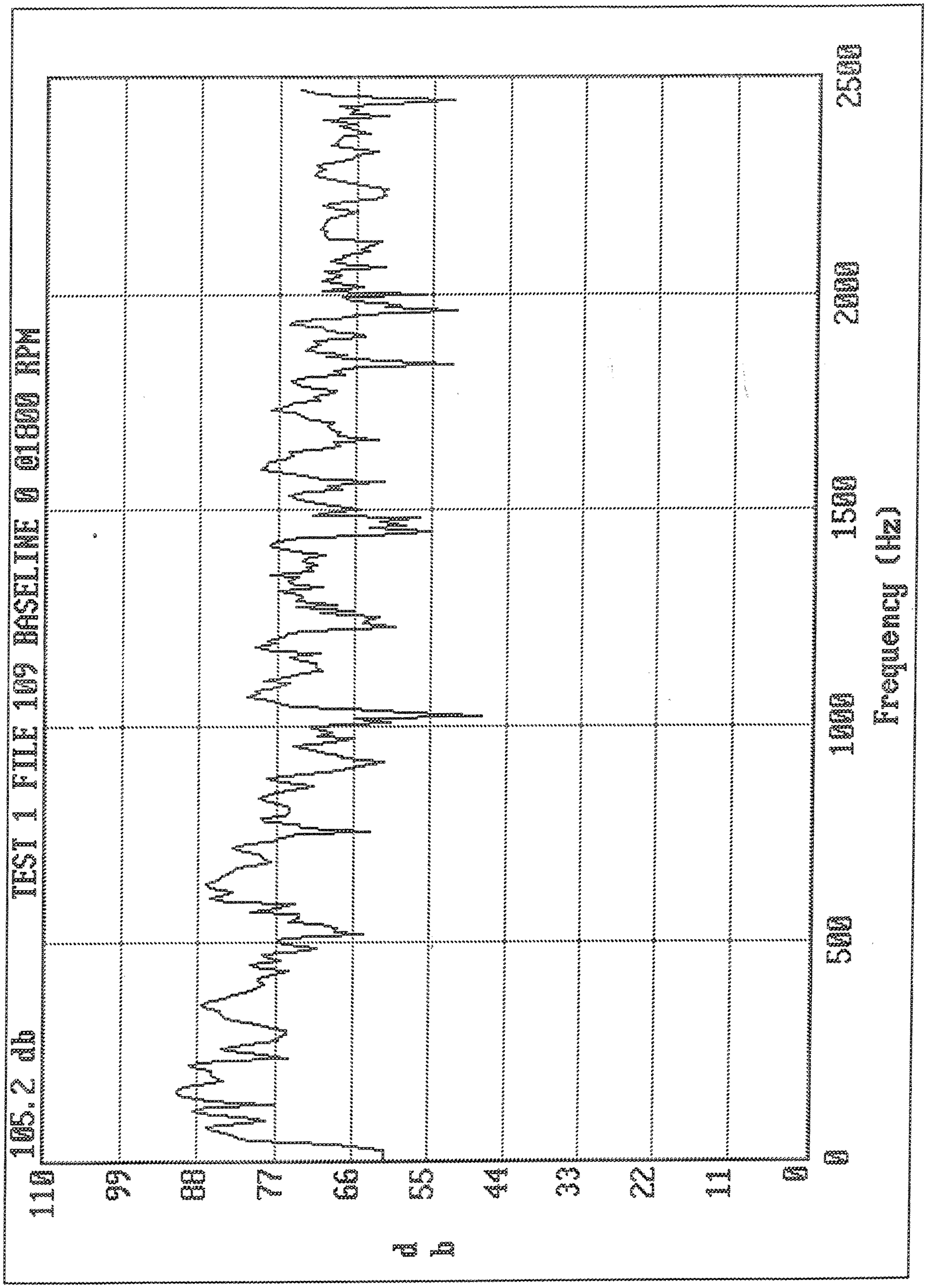
DYNO TEST 2 STRAIGHT PIPE DATA



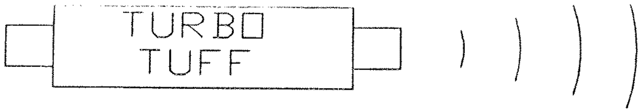
DYNO TEST 2 STRAIGHT PIPE DATA



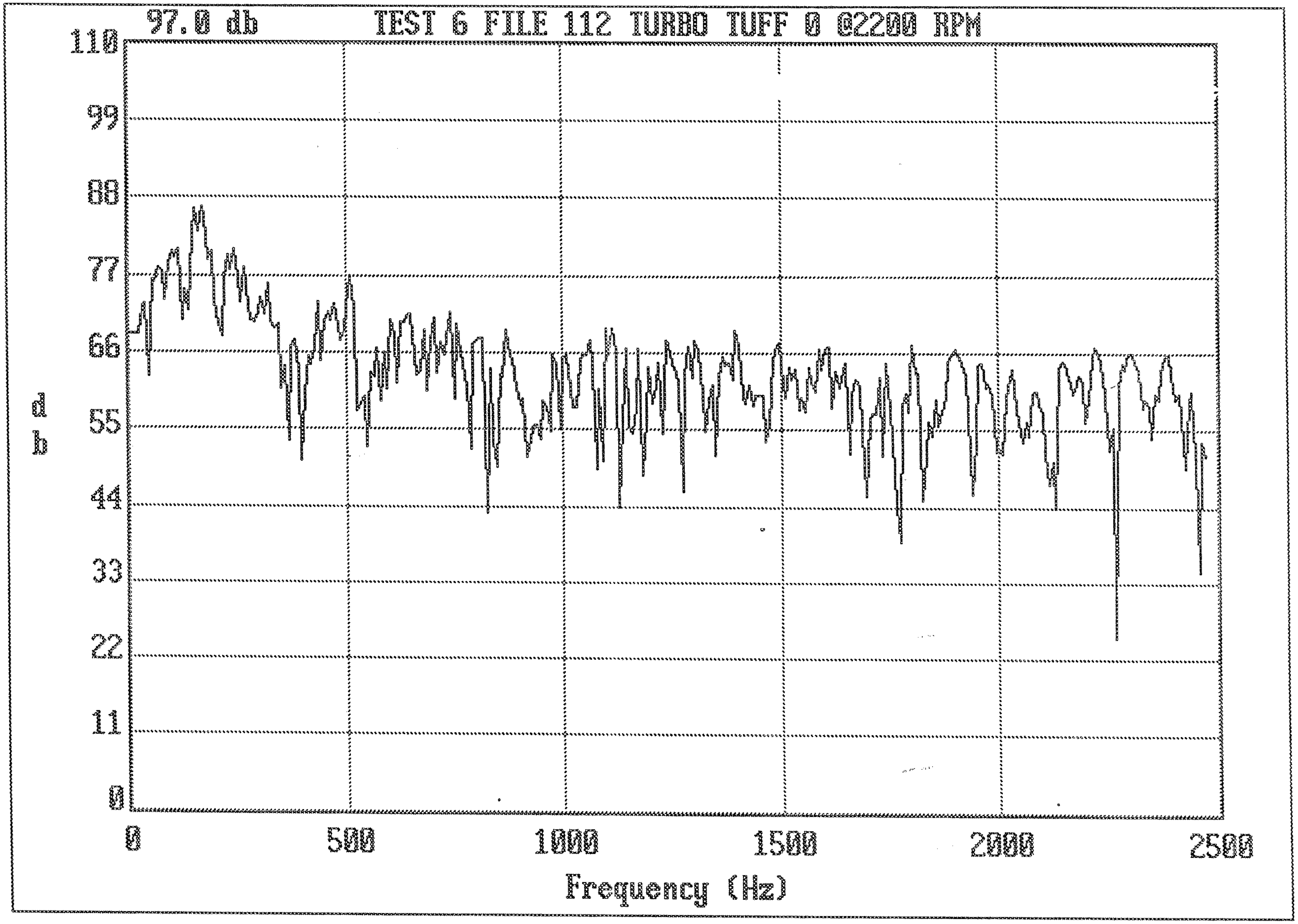

101.4 db
TEST 1 FILE 100 BASELINE 0 @1500 RPM
110
99
88
77
66
55
44
33
22
11
0
db
0
500
1000
1500
2000
2500
Frequency (Hz)



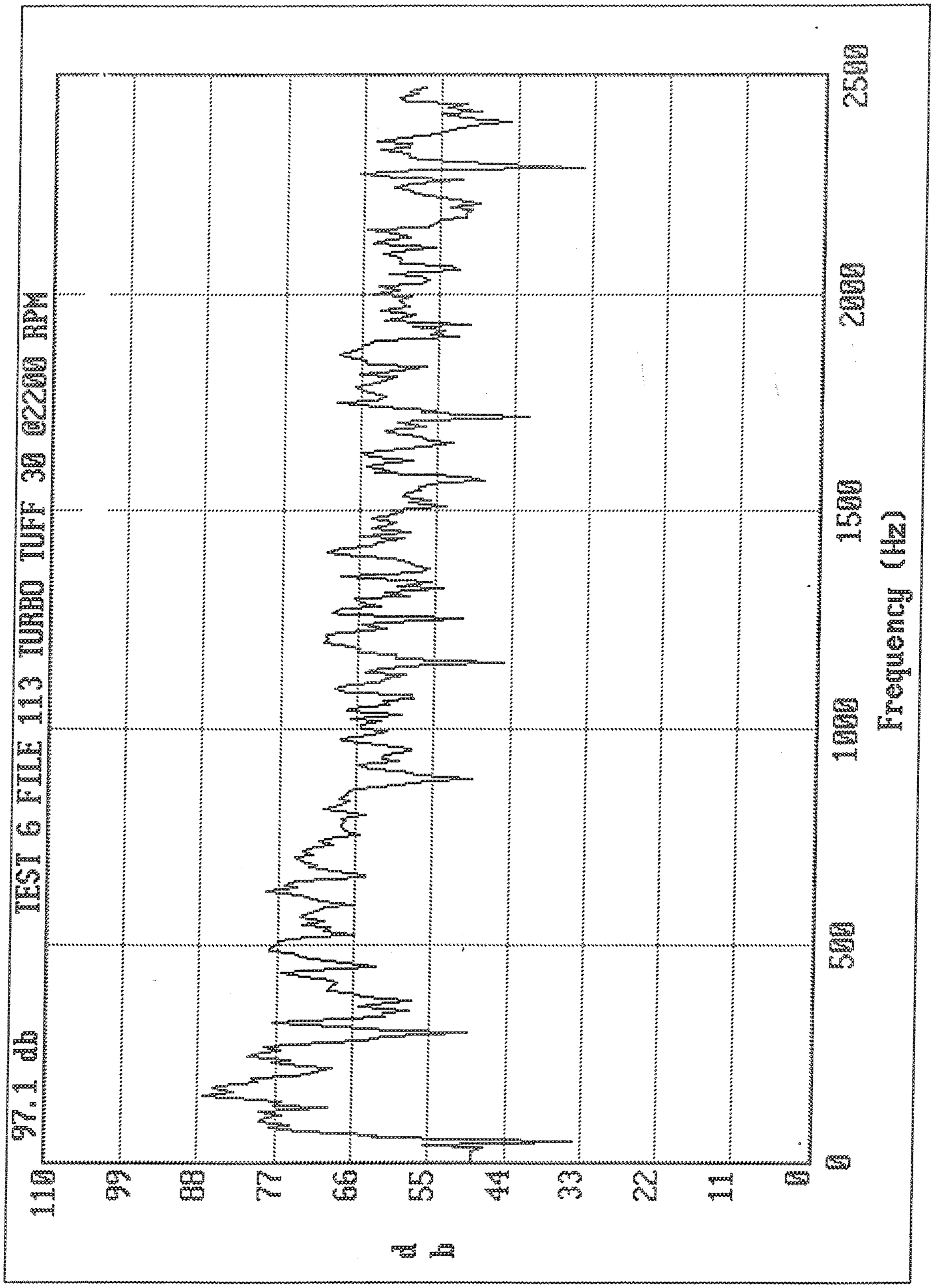
105.2 db
TEST 1 FILE 109 BASELINE 0 @1000 RPM
110
99
88
77
66
55
44
33
22
11
0
d
b
0
500
1000
1500
2000
2500
Frequency (Hz)

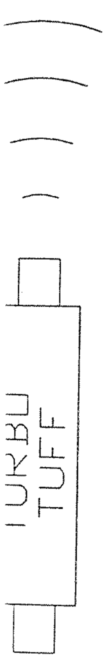


DYNO TEST 6 TURBO TUFF

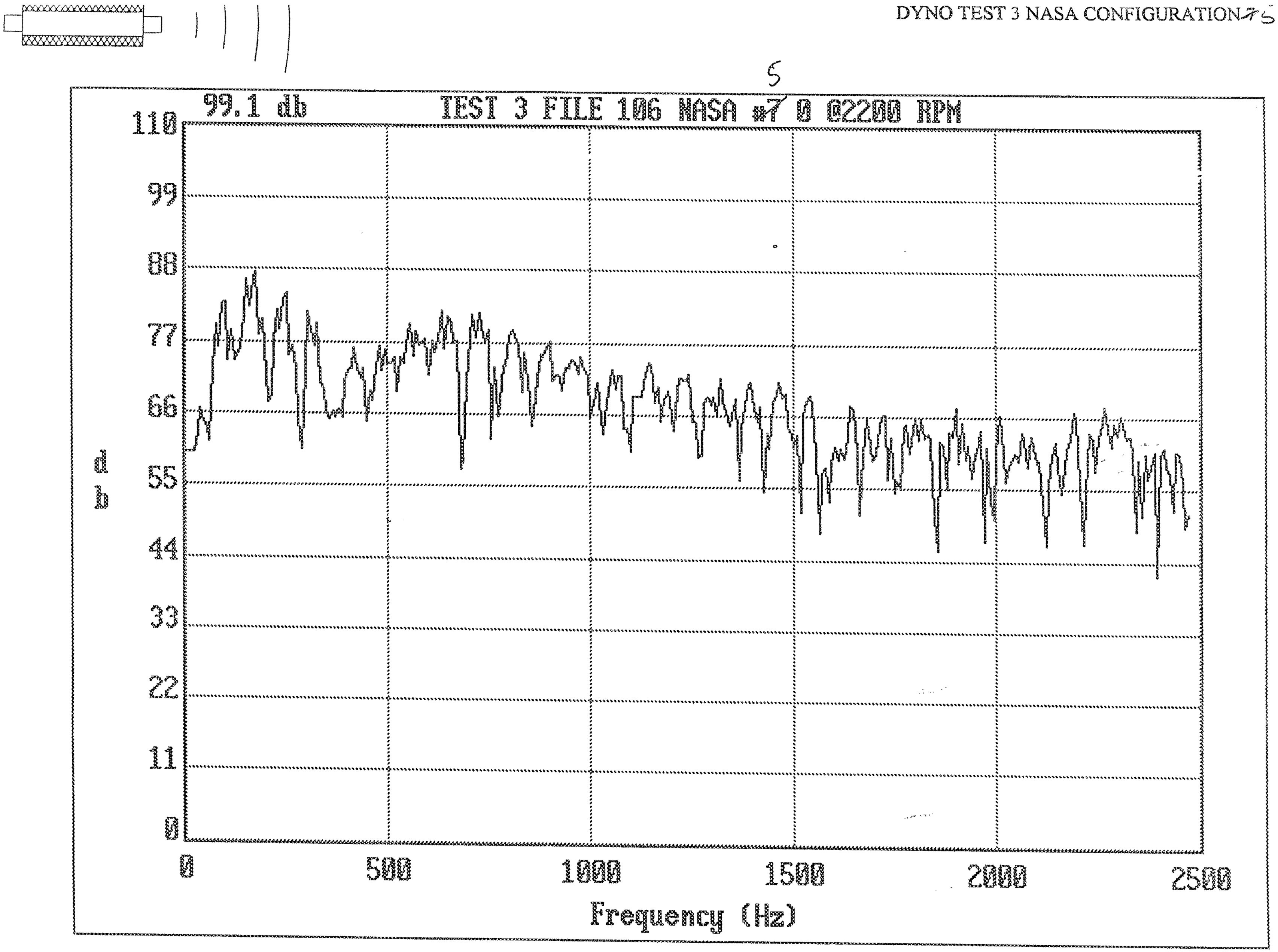


DYNO TEST 6 TURBO TUFF

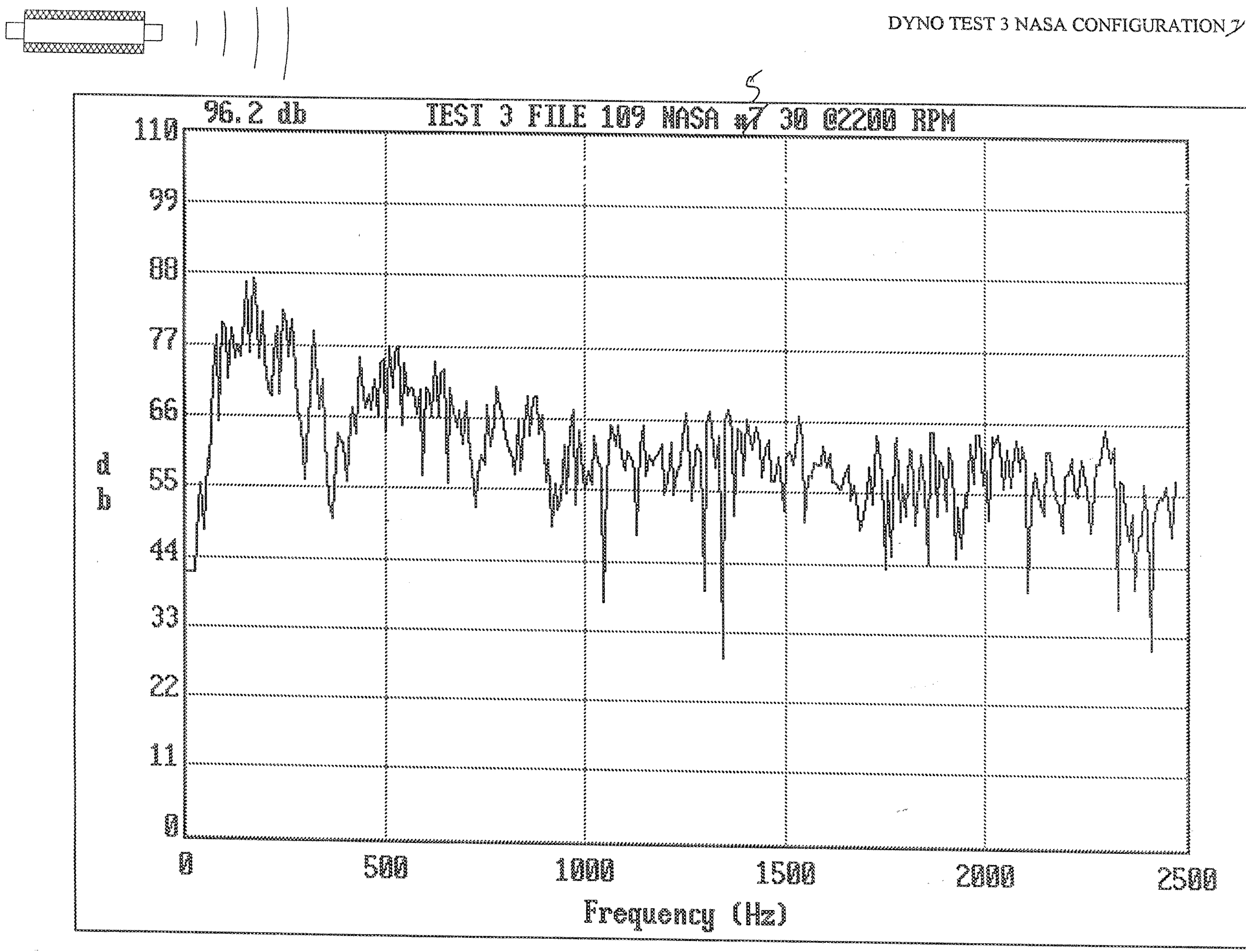




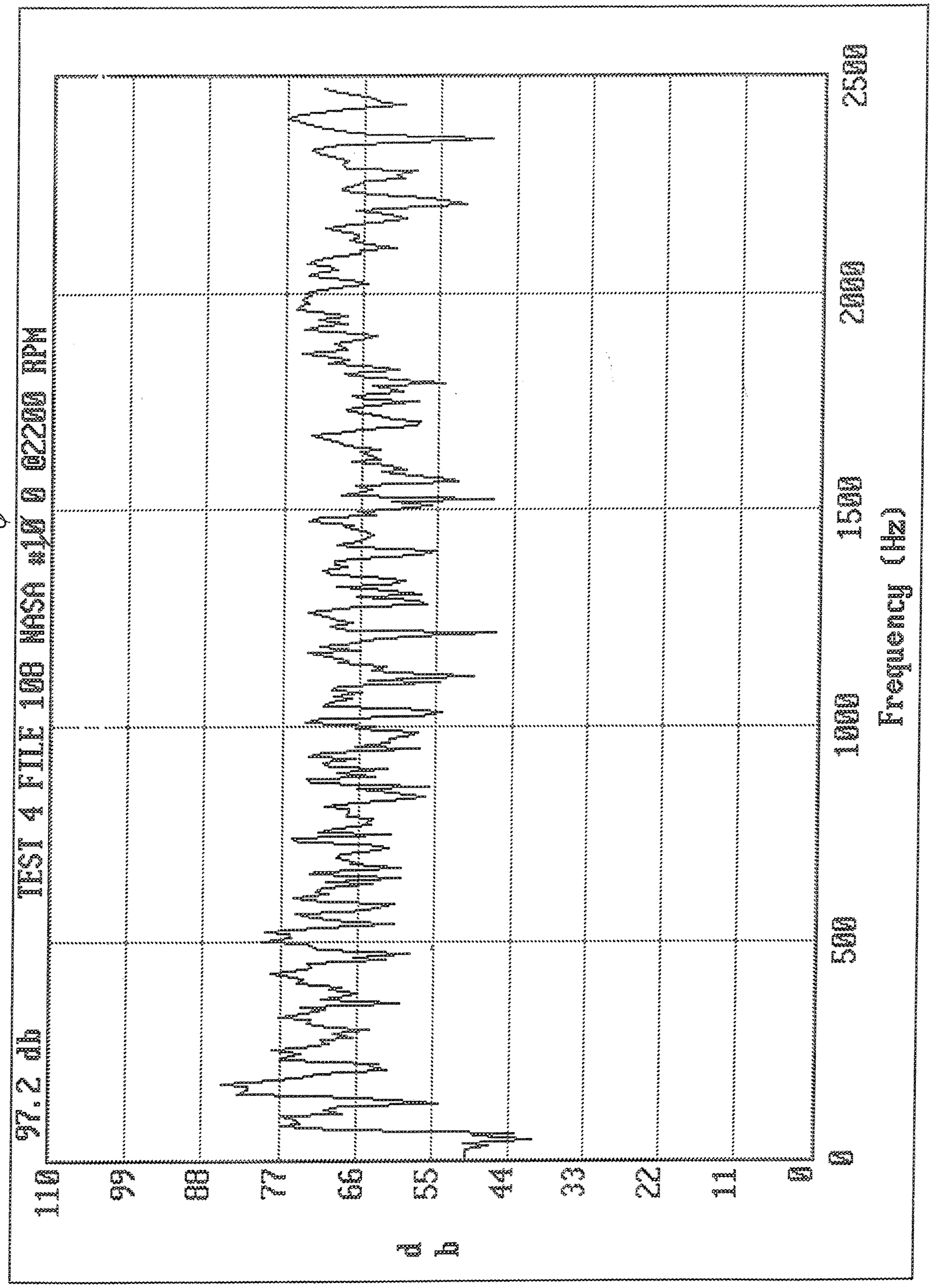
DYNO TEST 3 NASA CONFIGURATION #5

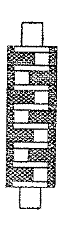


DYNO TEST 3 NASA CONFIGURATION ~~7~~ 5



DYNO TEST 4 NASA CONFIGURATION ~~10~~ 6





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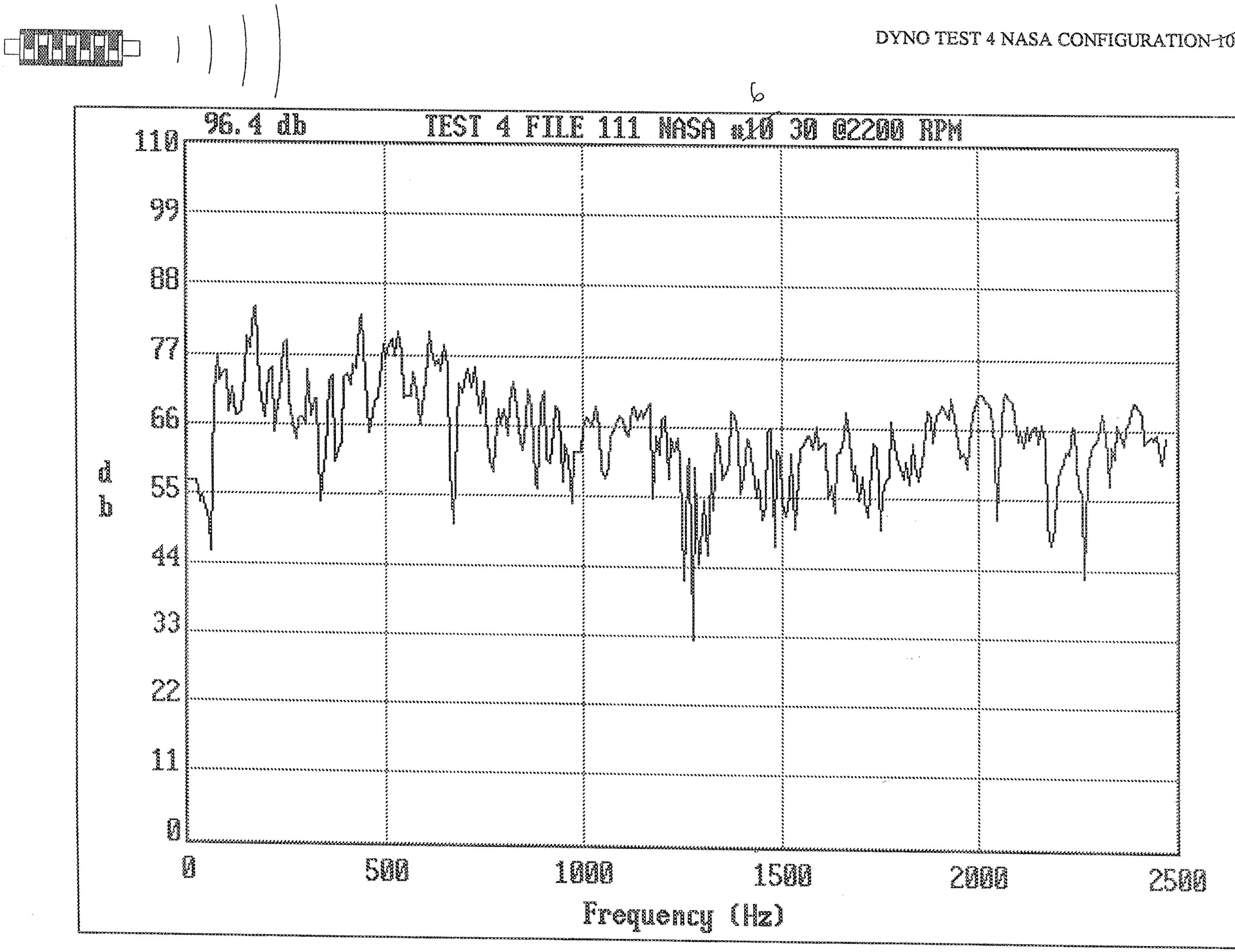

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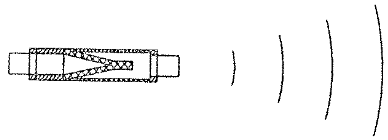

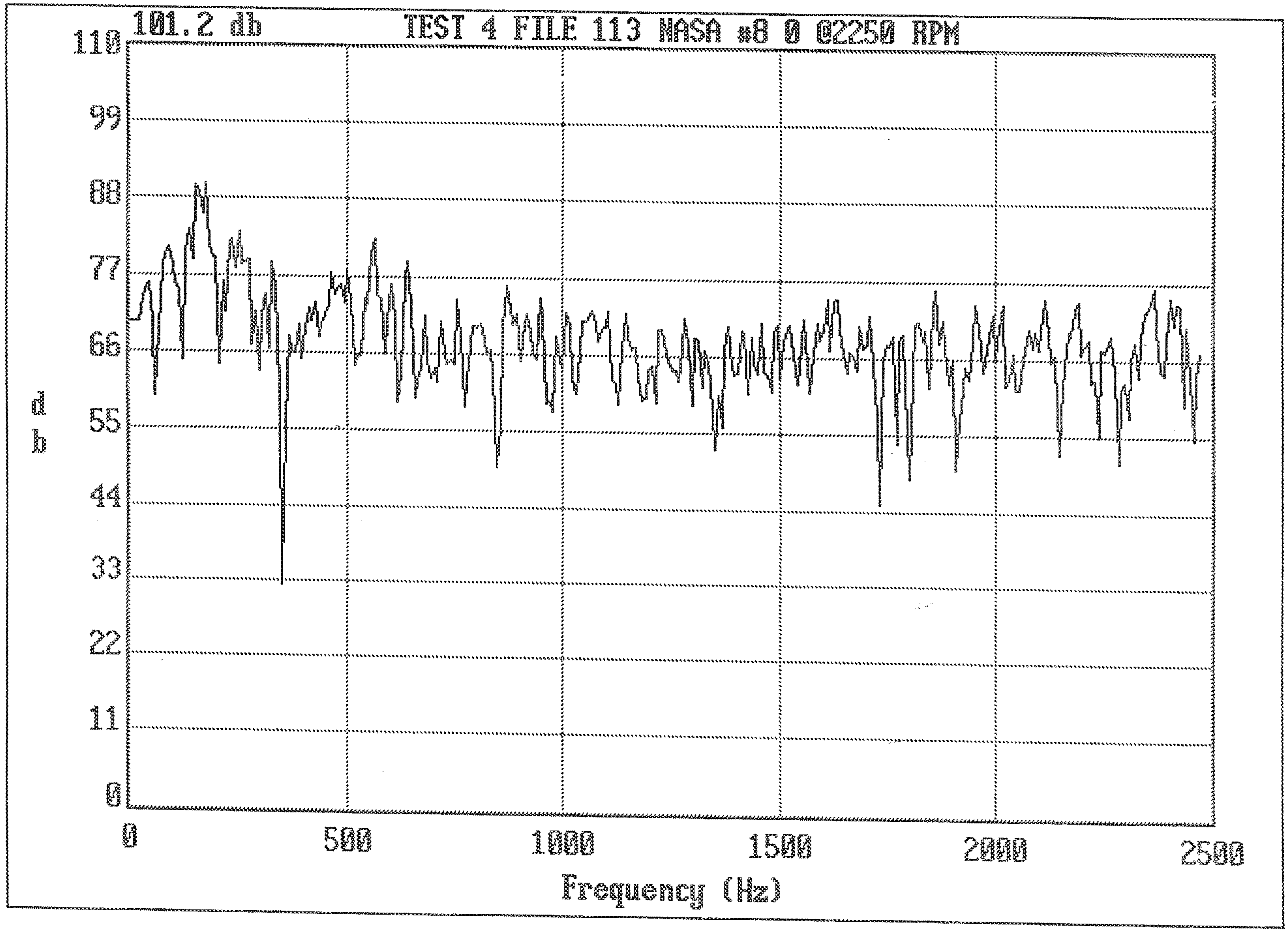

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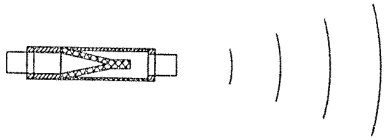

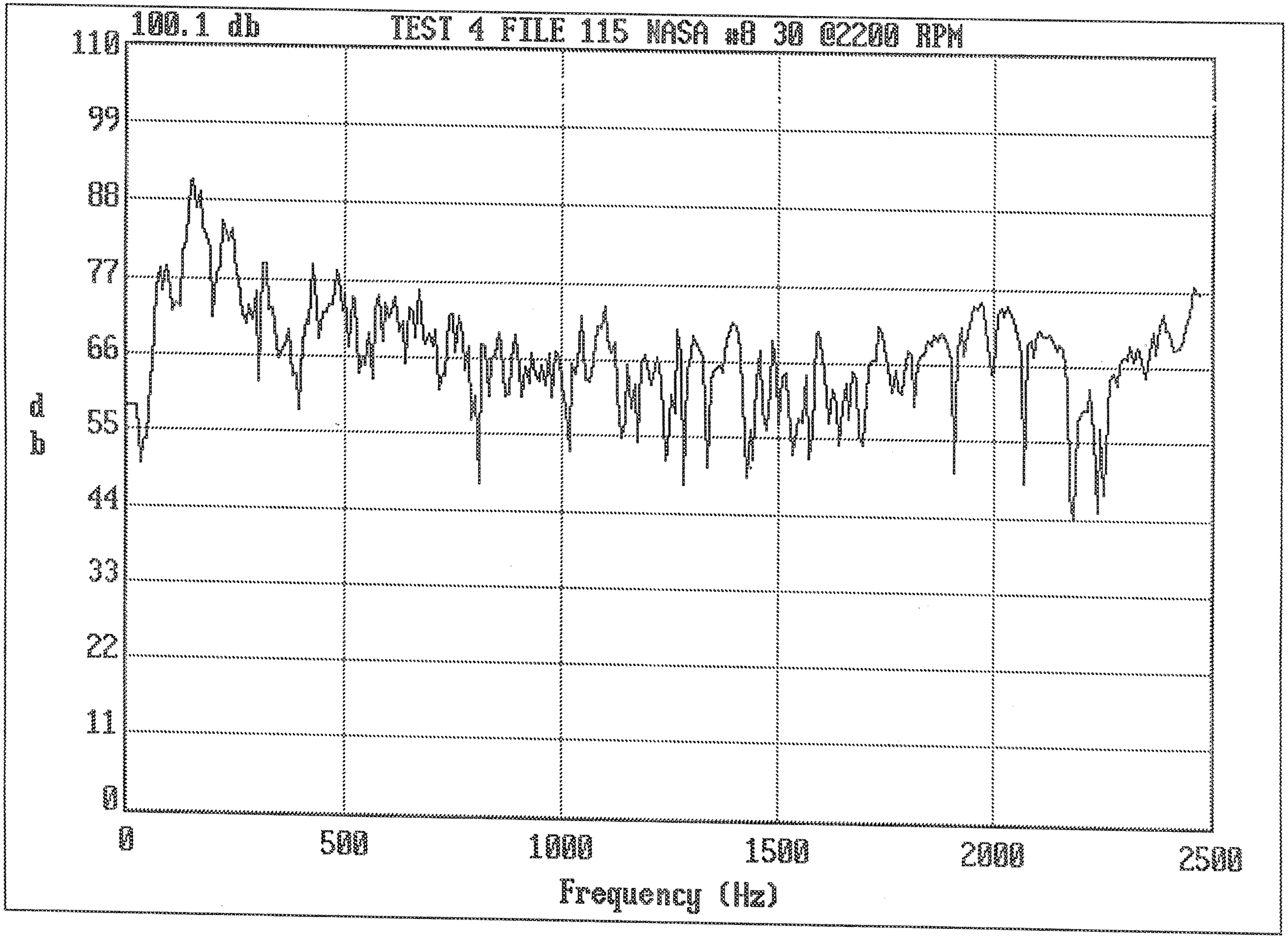

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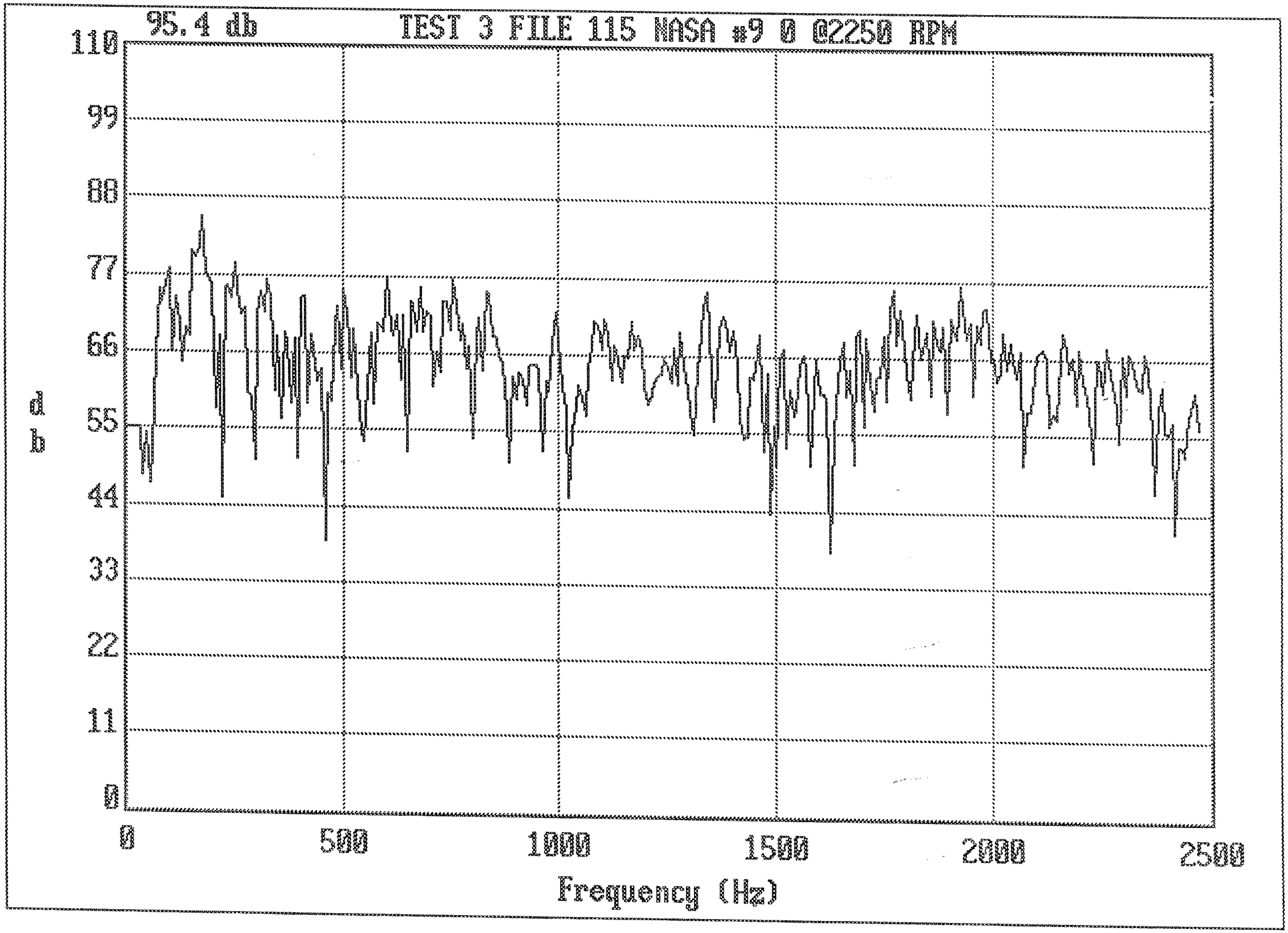

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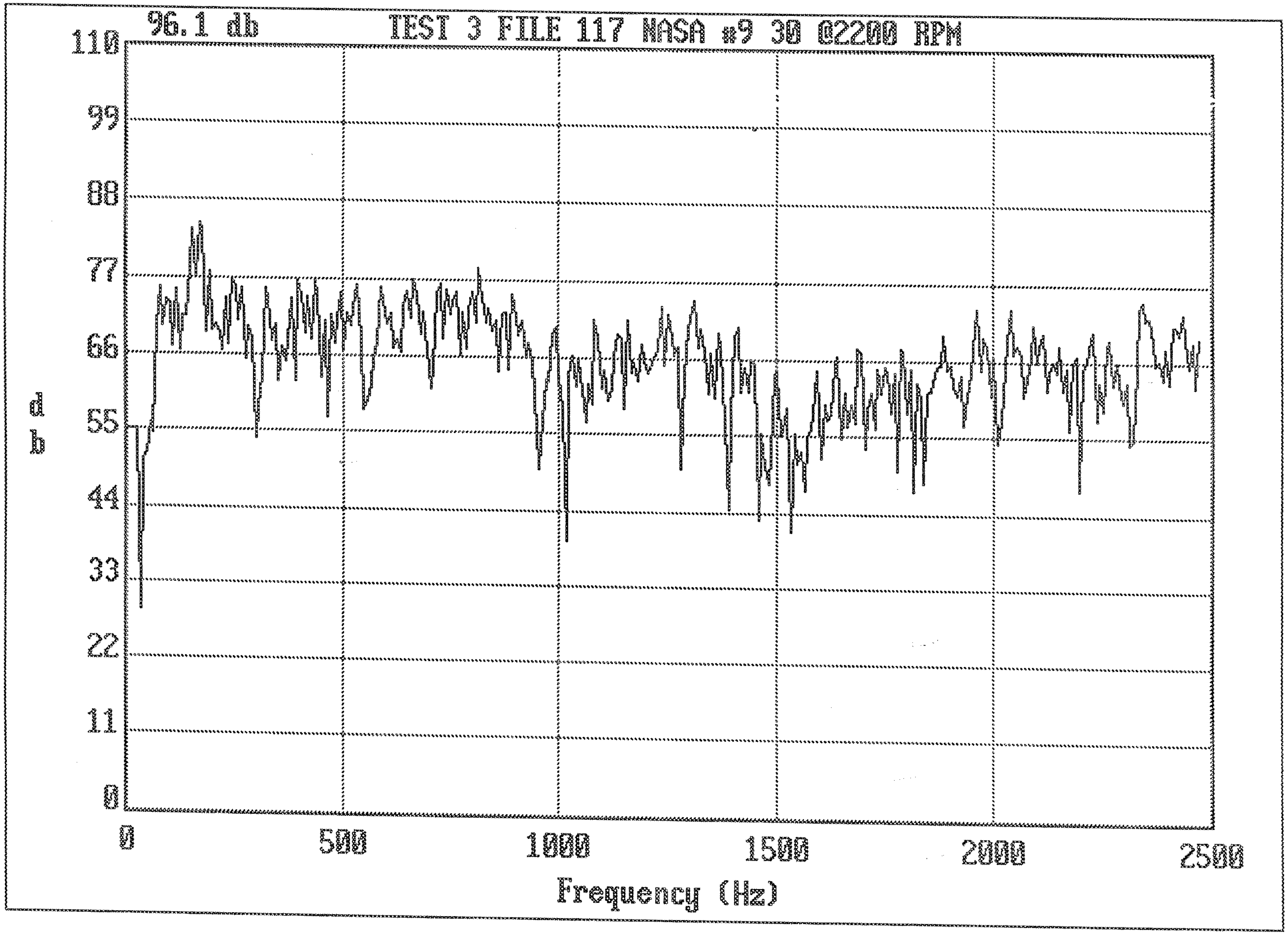

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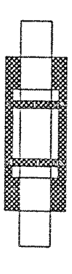

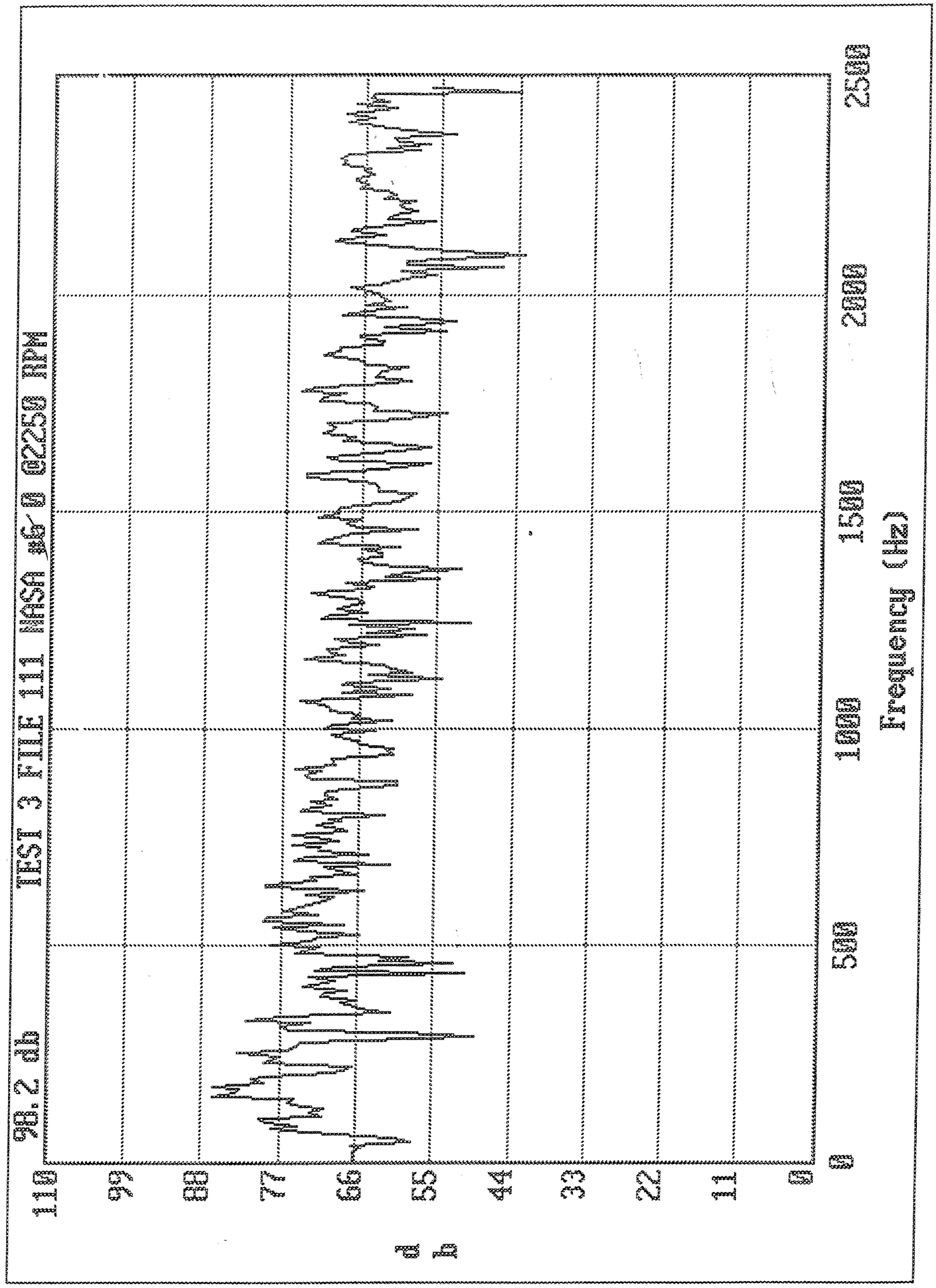

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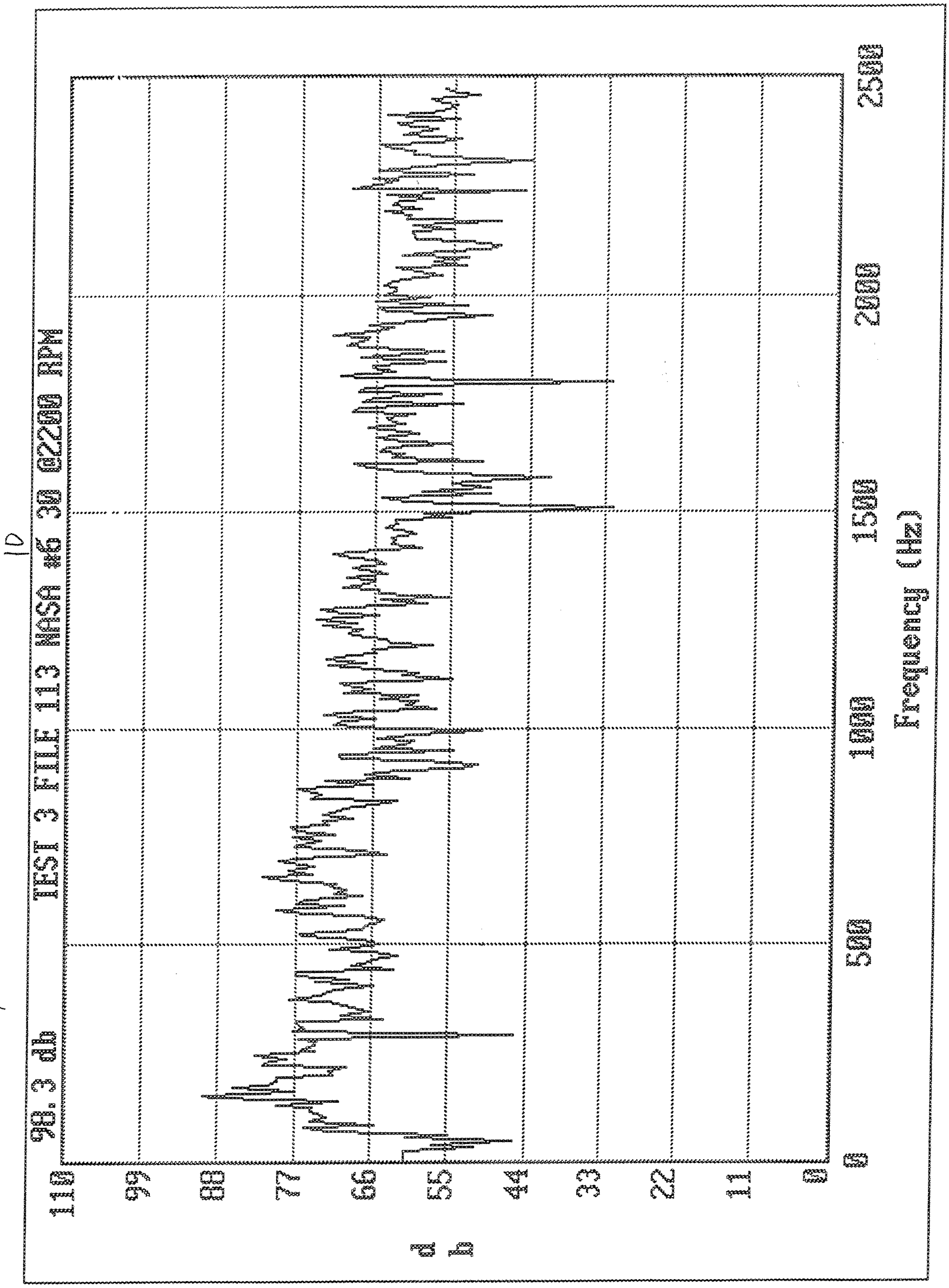

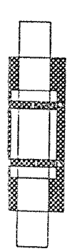

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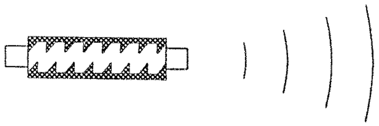

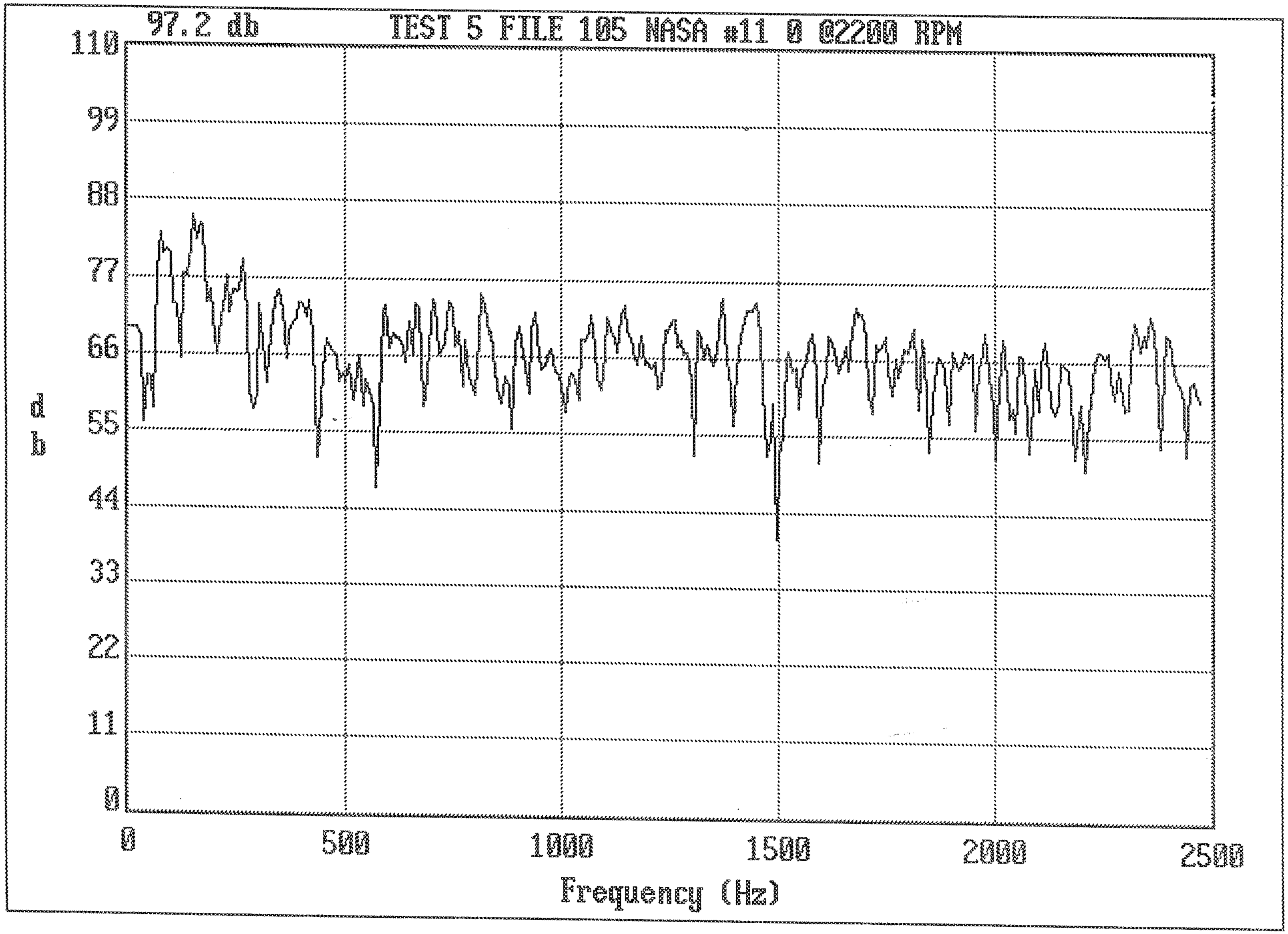

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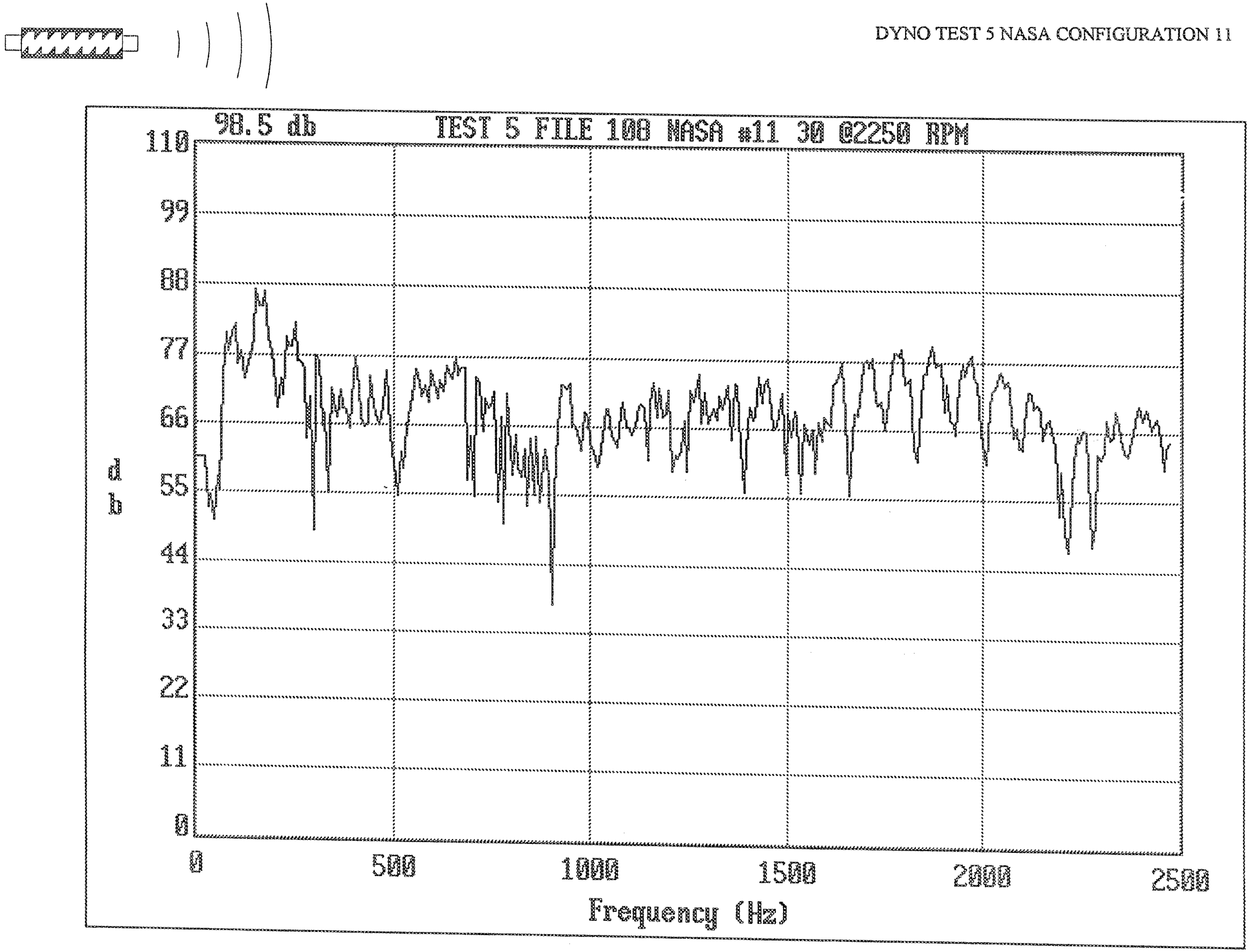

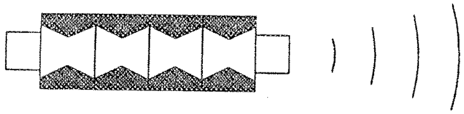

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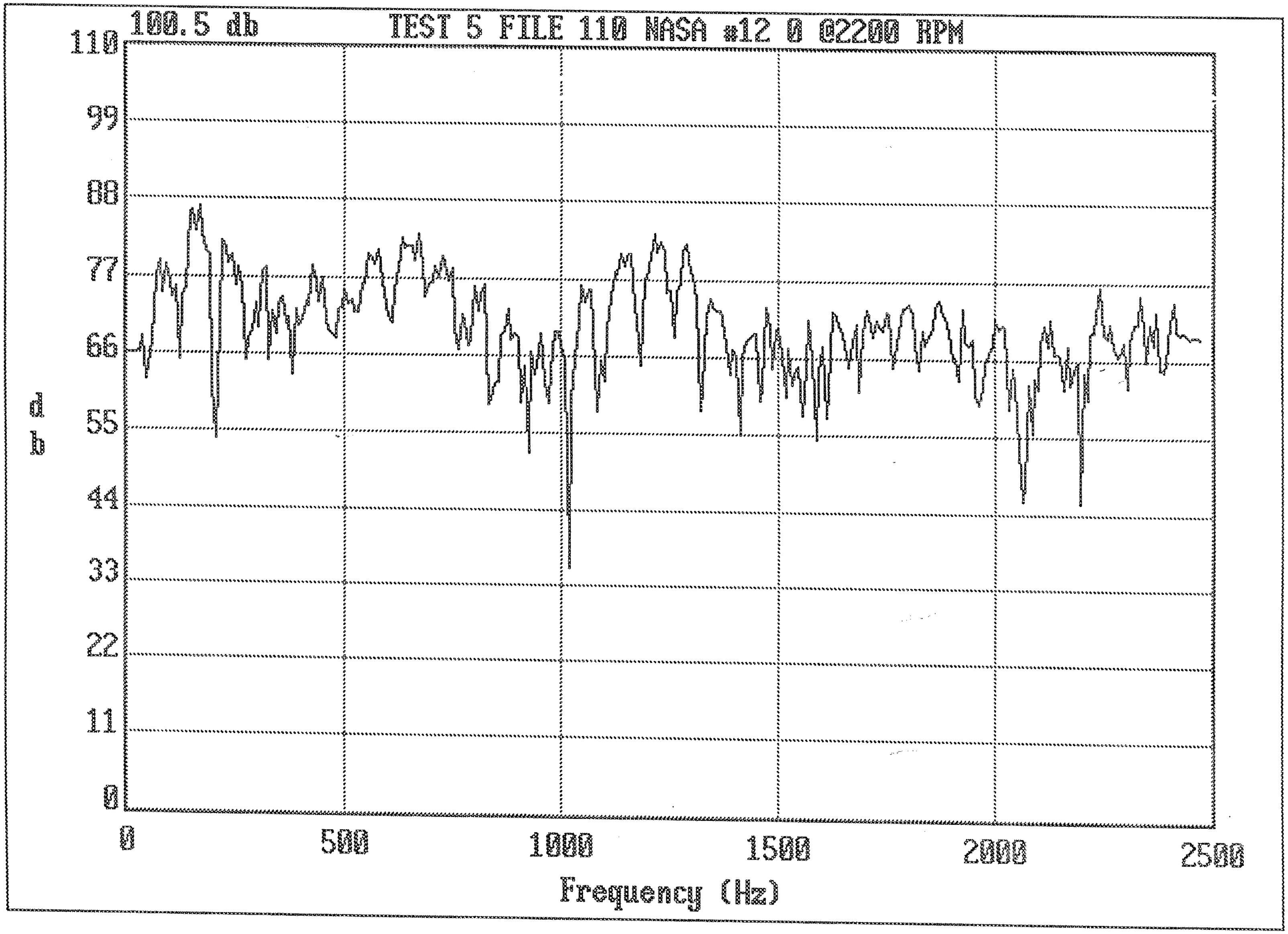

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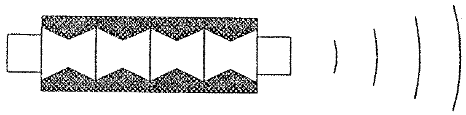

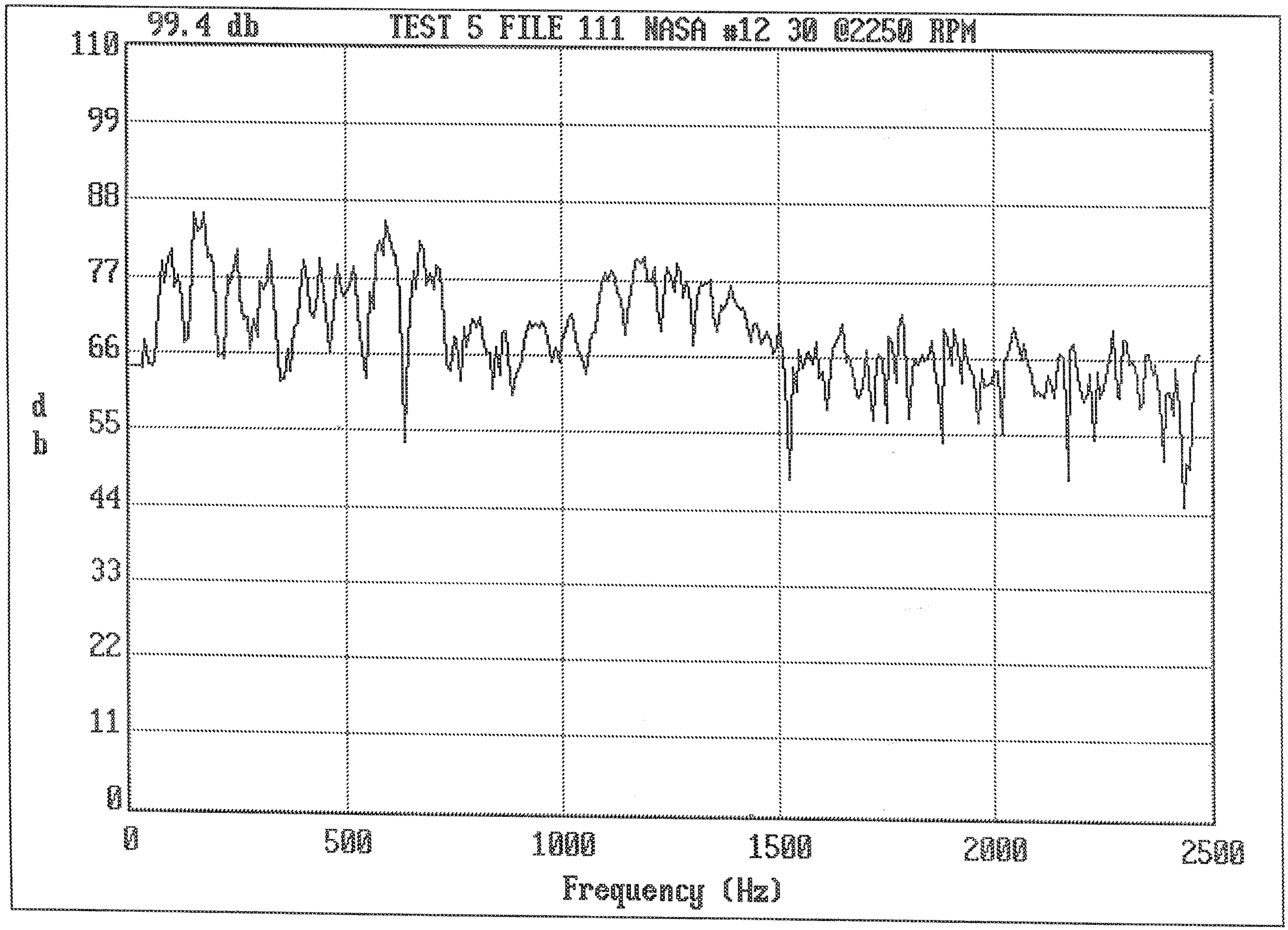

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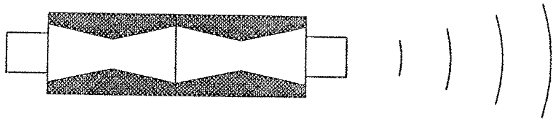

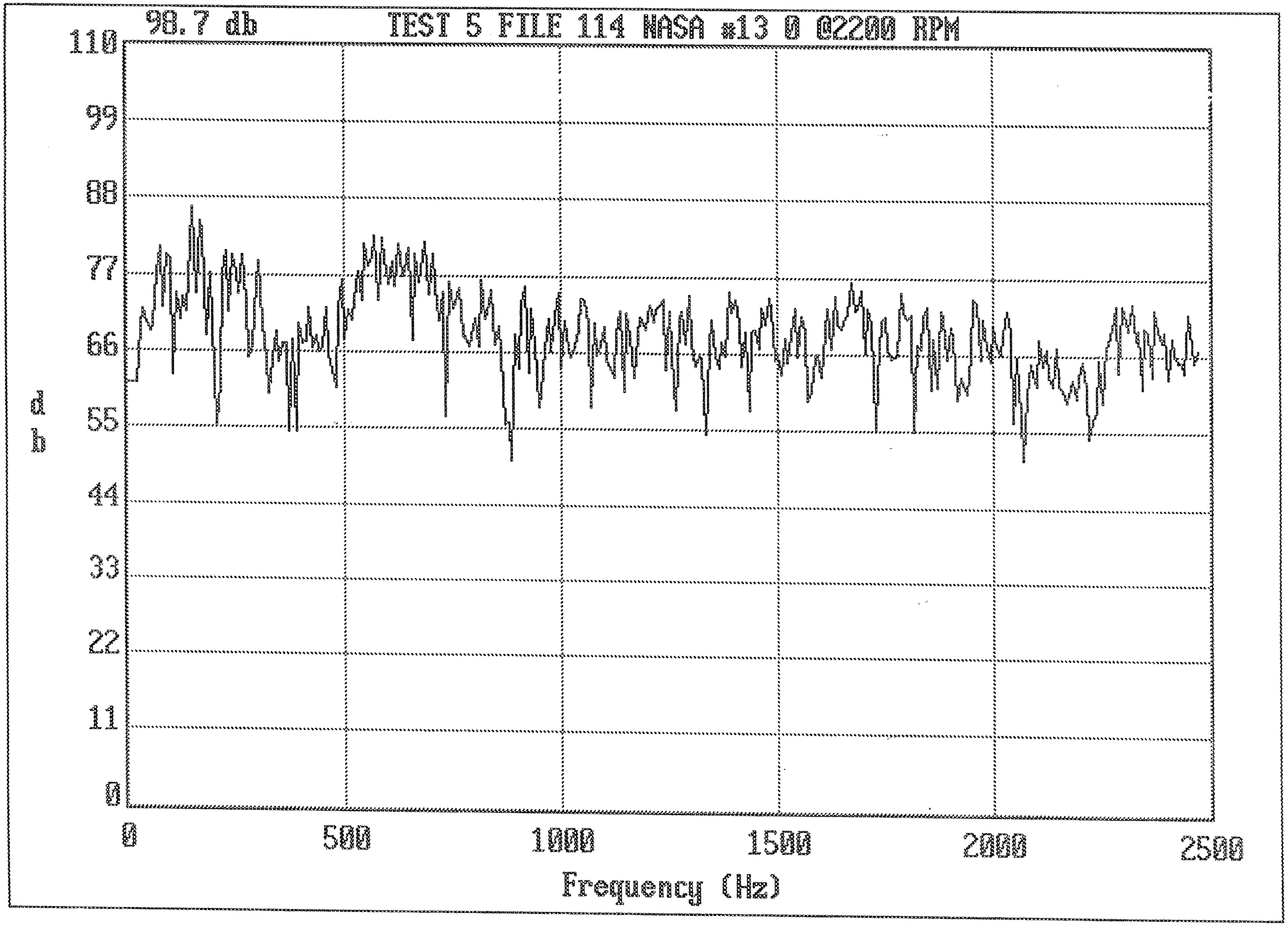

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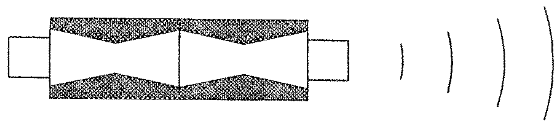

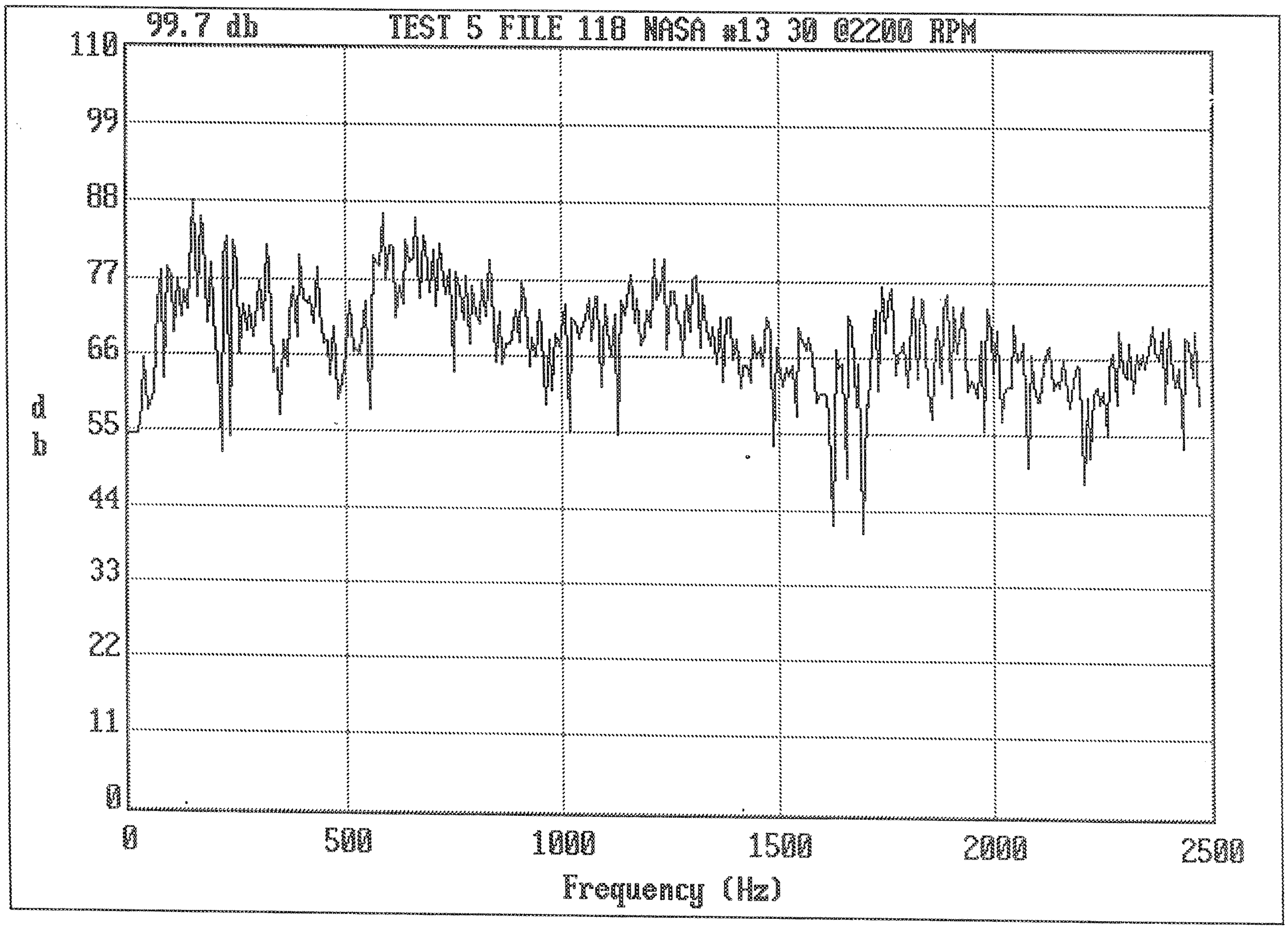

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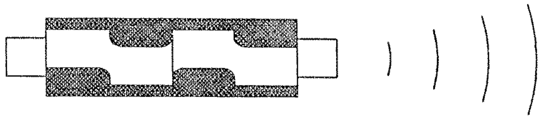

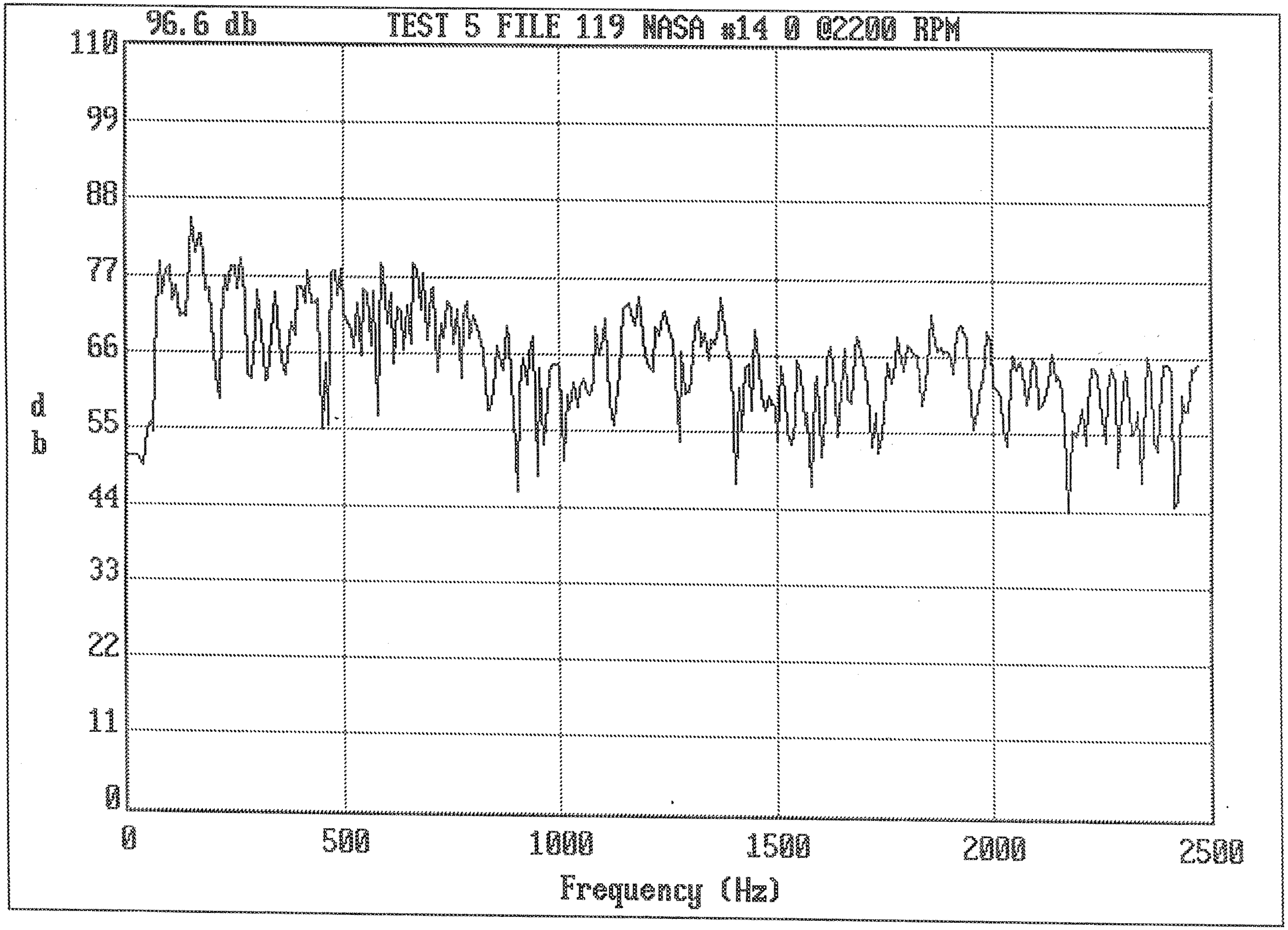

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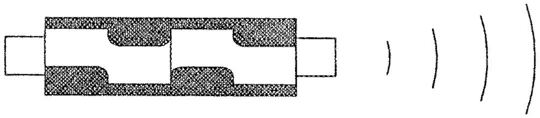

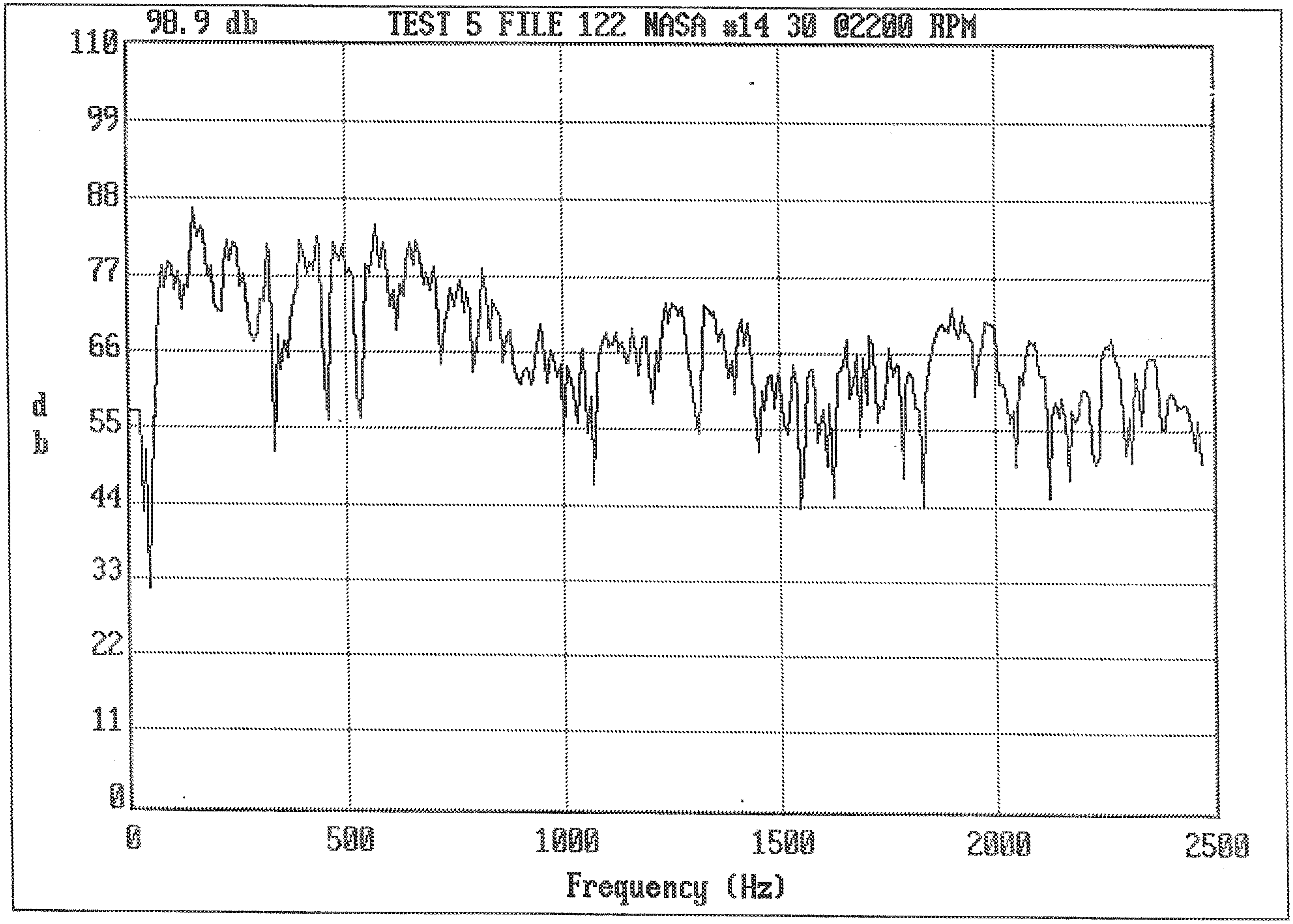

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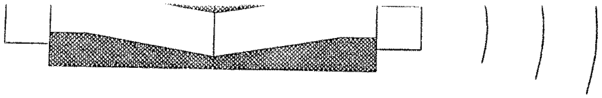

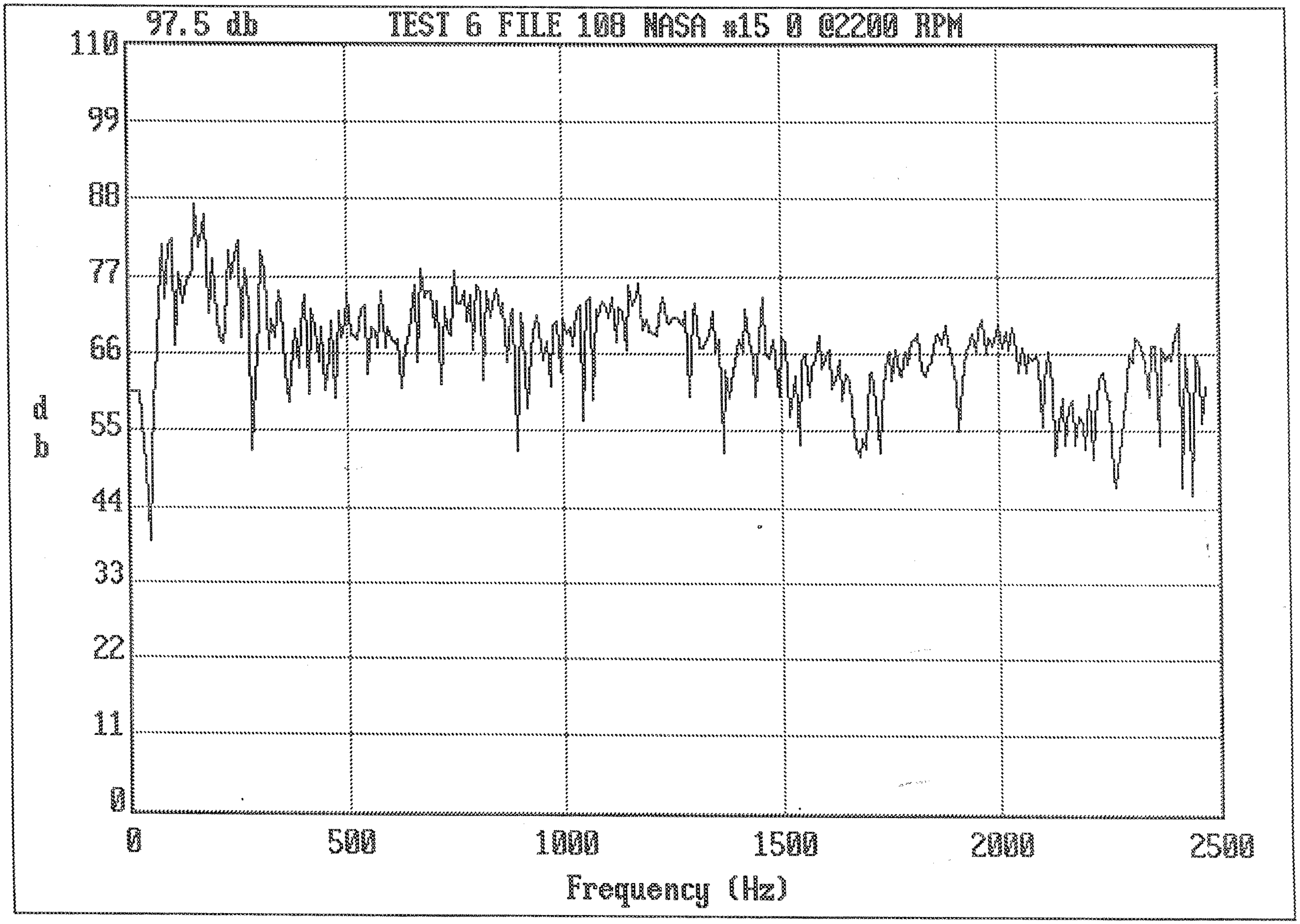

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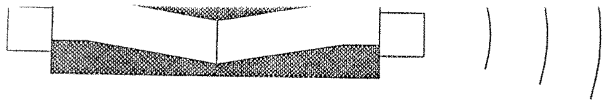

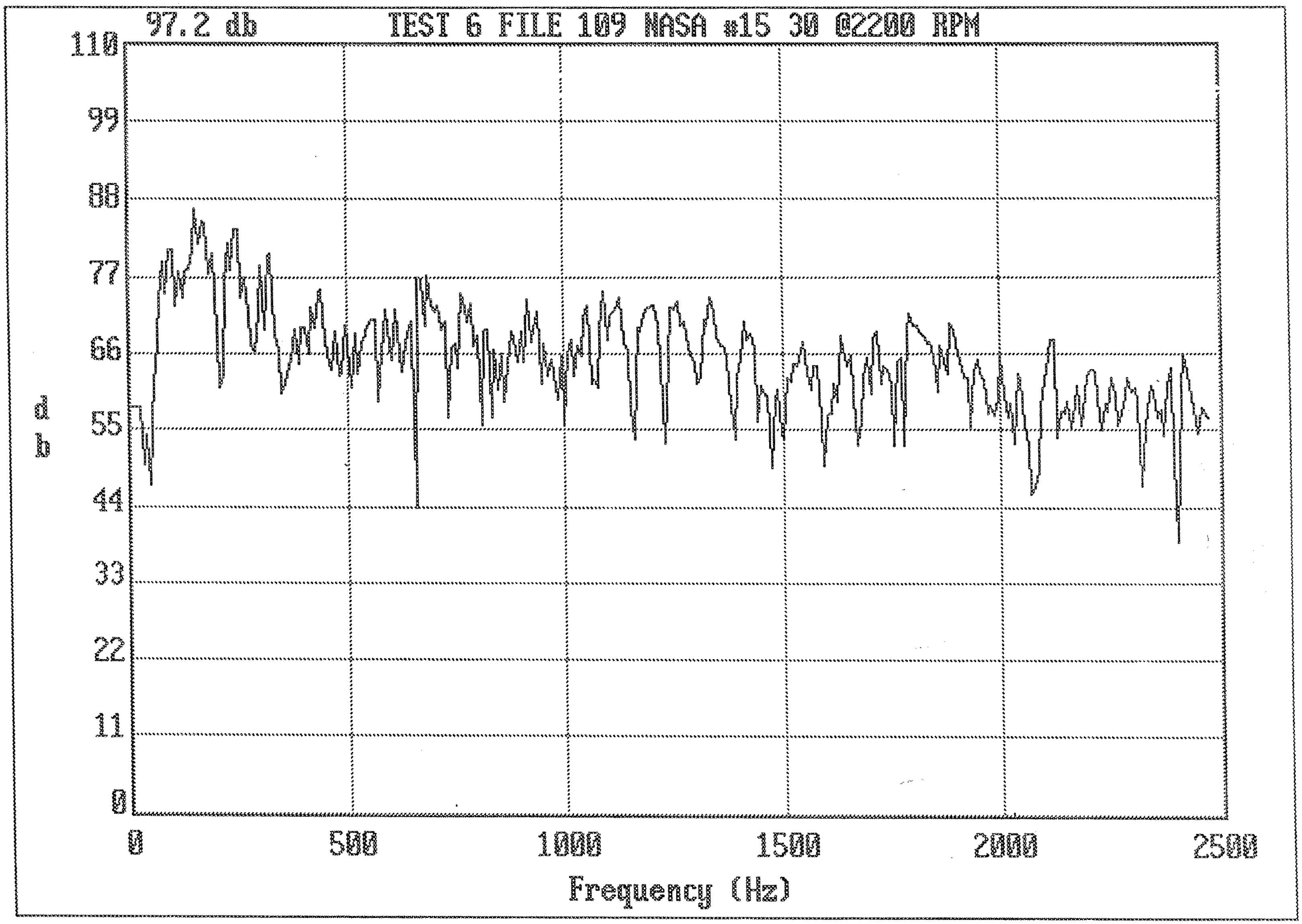

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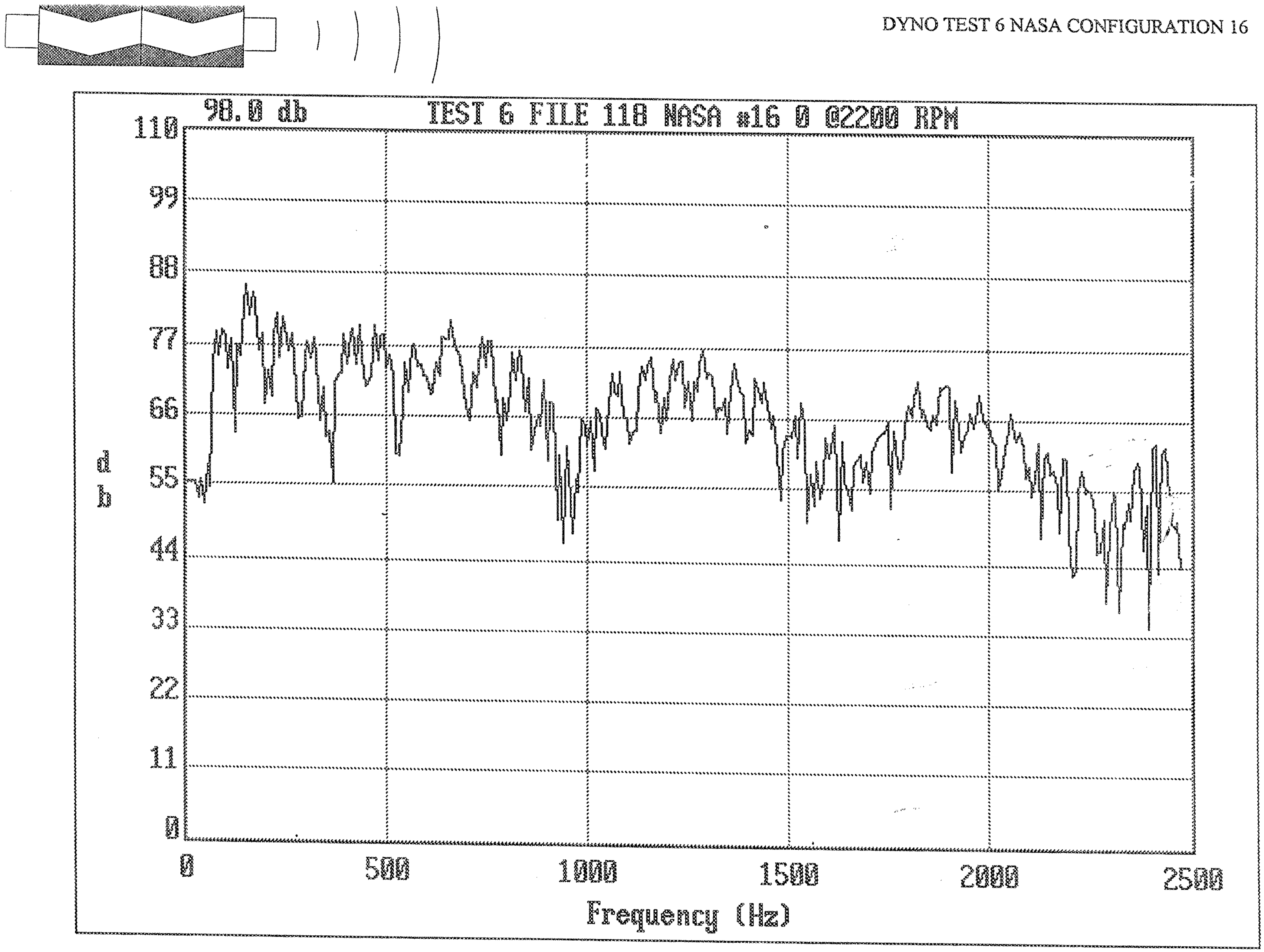

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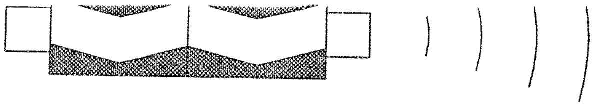

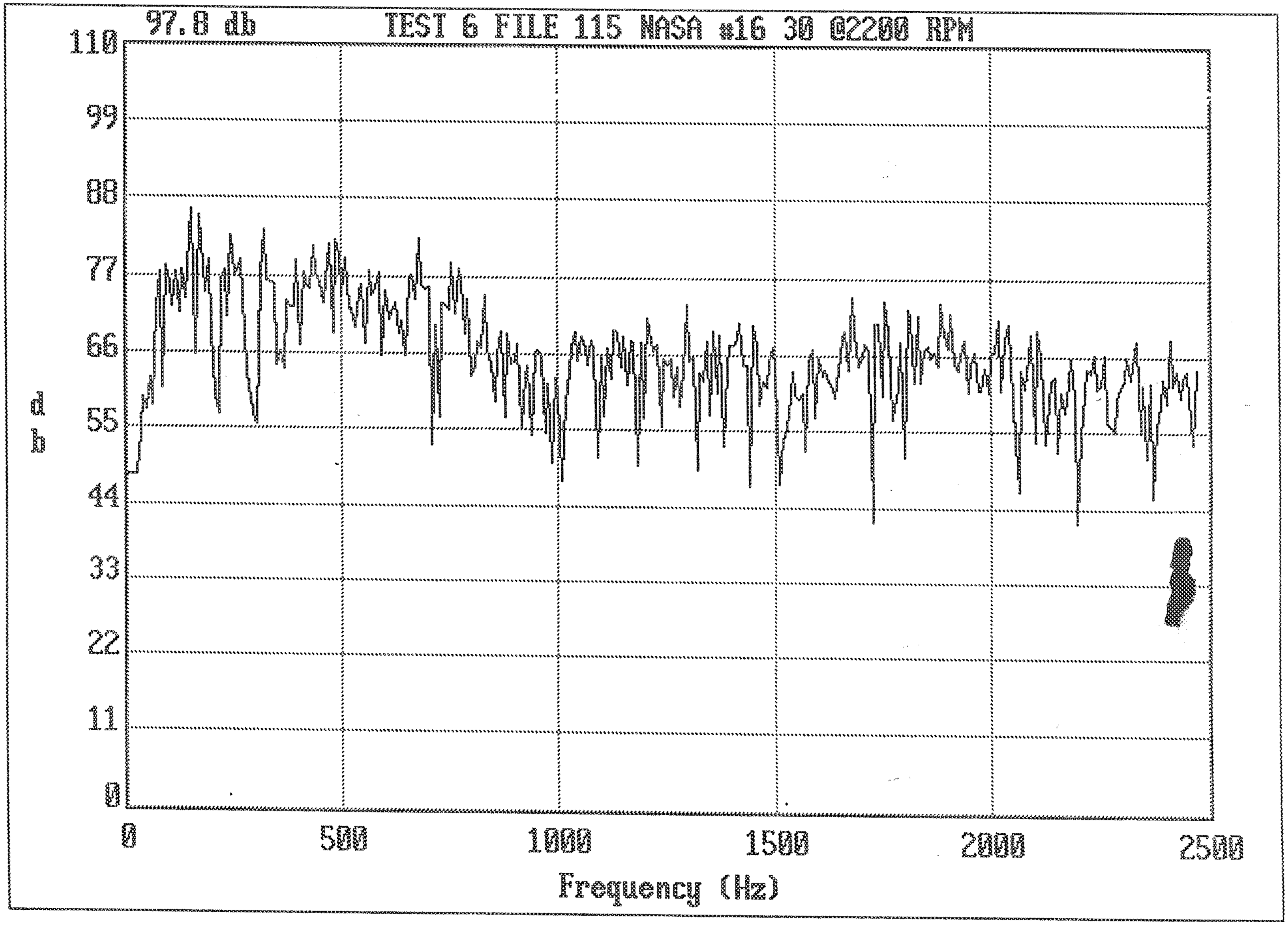

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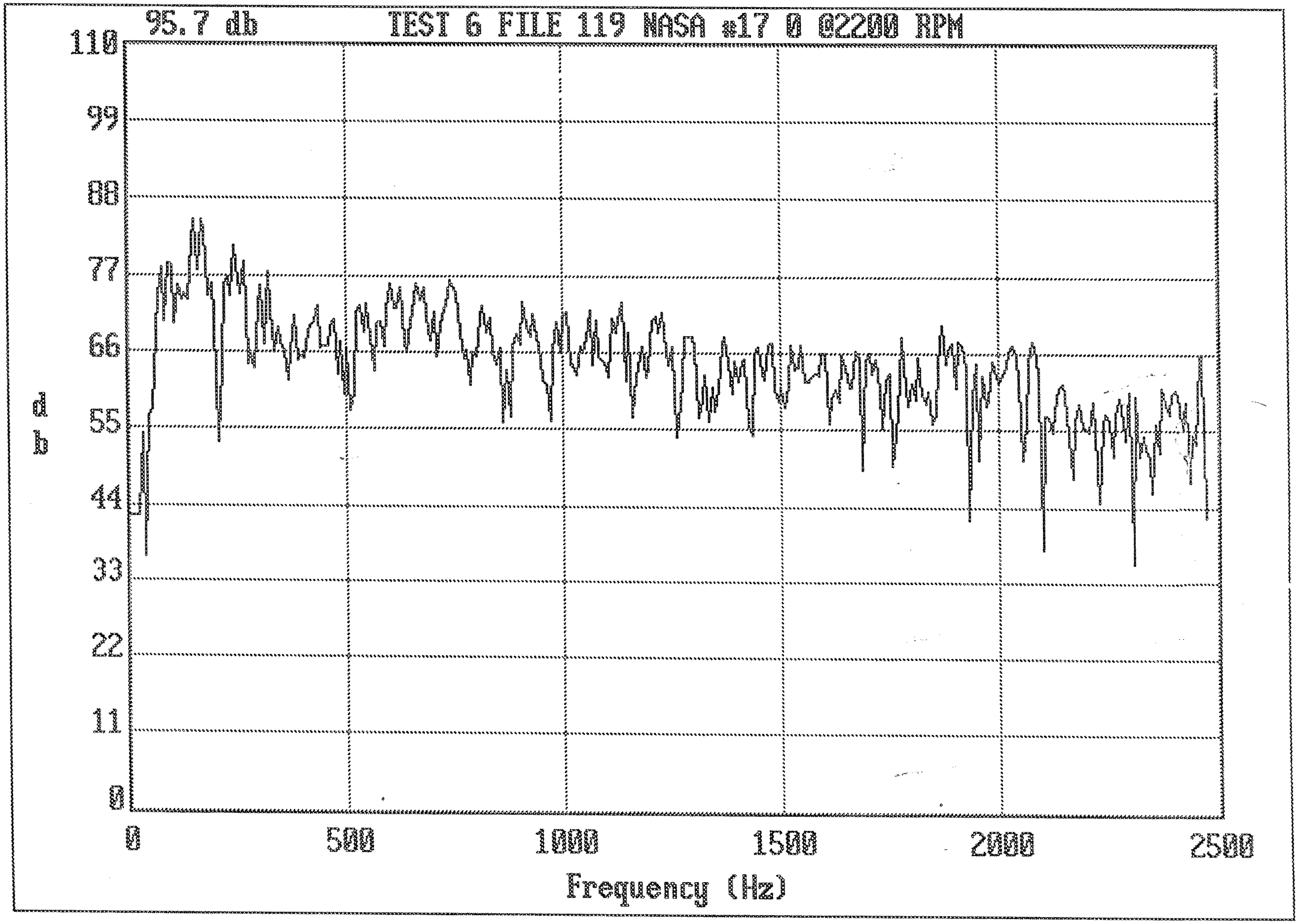

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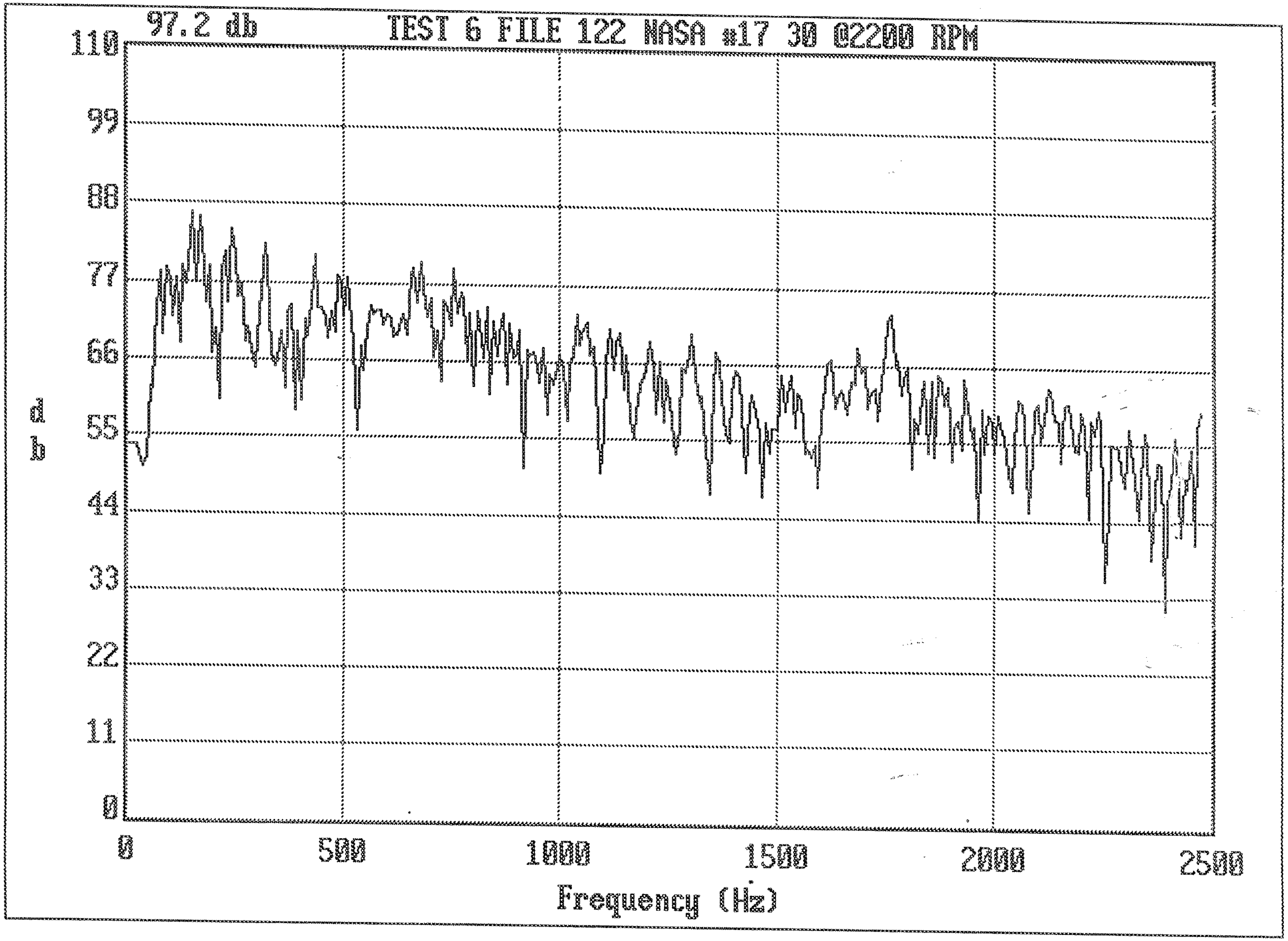

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13. ABSTRACT *(Maximum 200 words)*

In this project, durable, high temperature ceramic foams were evaluated as potential passive broadband noise absorber/baffle materials for reciprocating piston general aviation aircraft engines. In the Phase I project, a ceramic foam-based combined dissipative/reactive muffler design proved its potential for successfully reducing the size, weight, induced backpressure, and noise of general aviation aircraft engines. However, tuning the combined muffler design for specific engine noise reduction proved highly complex and difficult, requiring analytical tools that did not as yet exist. In Phase II, numerous test methods were developed to screen various newly developed ceramic foam-based muffler designs and evaluate their acoustic characteristics. More than 30 prototypes representing actual muffler designs and containing Ultramet ceramic foams were fabricated and characterized. Methods for acoustic evaluation included insertion loss bench, dynamometer, ground, and flight testing. Based on the results of these tests, Ultramet ceramic foams were shown to be generally effective as broadband noise absorbers at frequencies above 800 Hz, particularly for larger general aviation engines. The most promising ceramic foam-based muffler prototype reduced the noise emitted by a Continental O–200 engine by up to 14 A-weighted decibels (dB_A) relative to the stock exhaust system (a short, straight pipe). Varying the ceramic foam design parameters yielded variations of as much as 5 dB_A in the induced sound pressure levels, but did not affect the frequencies reduced. However, the backpressures induced by the majority of the ceramic foam muffler prototypes were well below maximum allowable levels. Given their light weight and compact size (including required canning and inlet/outlet pipes), these mufflers can be retrofitted under the cowlings of general aviation aircraft.

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